Architectural Design Strategies for Building-Integrated Photovoltaics in residential building renovation processes

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Preamble

This thesis falls within the context of the research project ACTIVE INTERFACES - Holistic operational strategies crossing over the obstacles for a large-scale advanced PV integration into urban renewal processes, financially supported by the Swiss National Science Foundation for Scientific Research (SNF) under the National Research Program (NRP) 70 - Energy Turnaround.

ACTIVE INTERFACES is an interdisciplinary project involving several research groups in Switzerland. The main aim is to overcome existing obstacles to promote the integration of photovoltaic (PV) elements into urban renewal processes. In this context, this thesis contributes to this goal by providing a methodology to help architects (designers) and local authorities (decision-makers) introduce Building-Integrated photovoltaics (BIPV) elements in the design process of renovation strategies at the building scale.

This thesis has benefited from its own autonomy thanks to the complementarity between the different research groups involved, and due also to the role of the Laboratory of Architecture and Sustainable Technologies (LAST), which is the initiator and coordinator of the project.

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Abstract

Tomorrow's European cities are already largely built, as much of the existing building stock – with a low level of energy performance – will still be standing in 2050. Urban renewal processes therefore play an essential role towards their sustainable transition. In this context, Building-integrated photovoltaic (BIPV) systems can potentially provide a crucial contribution to achieve current energy and mid- to long-term carbon targets based on the 2'000-Watt society concept in Switzerland, and to fulfil the objectives of the energy turnaround for 2050. Functioning both as envelope material and electricity generator, BIPV systems can simultaneously reduce the use of fossil fuels and greenhouse gases (GHG) emissions, while providing savings in materials and electricity costs. These are precisely the objectives of most European energy directives, from zero- to positive-energy buildings. However, despite continuous technological progress and increasingly favourable economic conditions, the significant assets of BIPV remain broadly undervalued in the current practice. Various obstacles related among others to technology choice, low demand (which induces small volume production of BIPV products), and lack of information and of aesthetically convincing renovation examples, tend to increase the costs and prevent the acceptance of BIPV solutions.

Considering that BIPV can be integrated into the design process, but in a case-specific rather than in a systematic way, this thesis aims at offering support to stakeholders – especially architects – involved in the design process of renovation projects. Focusing on an integrated architectural design process for addressing renovation projects of residential buildings, the approach involves four main phases: (1) building stock analysis to identify representative (archetypal) situations, (2) detailed analysis of real case studies, (3) architectural design of different renovation scenarios using BIPV strategies, and (4) multi-criteria assessment of each scenario. The concrete contributions of this thesis are twofold. First, a set of integrated design strategies – illustrated through real case studies – is defined to promote the integration of BIPV in urban renewal processes. It integrates: (i) passive strategies, to improve the envelope through low embodied-energy materials and construction systems, (ii) BIPV strategies, using innovative photovoltaic products as a new material for façades and roofs, and (iii) active strategies, adapting heating, ventilation, and air conditioning (HVAC) systems to improve the efficiency of the BIPV installation and reduce the dependence on feed-in-tariffs to ensure the profitability of investments. Second, a multi-criteria assessment methodology is developed to compare the different intervention scenarios, based on a qualitative and quantitative approach. The proposed workflow thus allows comparing different design solutions in terms of BIPV performance, final energy balance, Life-Cycle Analysis (LCA) and Cost (LCC) of the whole renovation process. This approach shall provide architects and engineers with advanced BIPV renovation strategies that depend on the building typology, the architectural design goals, and the level of intervention, thus supporting and inspiring them towards a low-carbon built environment.

Keywords: building renovation | building-integrated photovoltaics (BIPV) | integrated design | multi-criteria assessment | sustainable architecture | life-cycle analysis | low-carbon buildings | carbon neutrality.

Résumé

Les villes européennes de demain sont déjà en grande partie construites, étant donné qu'une large part du parc bâti actuel – caractérisée par une faible performance énergétique – sera toujours présent en 2050. Le renouvellement urbain joue donc un rôle essentiel en vue de leur transition vers la durabilité. Dans ce contexte, les installations photovoltaïques intégrées au bâtiment (BIPV) ont le potentiel de contribuer de façon significative à l'atteinte des objectifs d'efficience énergétique et de faible empreinte carbone, à l'instar de ceux inhérents au concept de la Société à 2'000 Watts en Suisse. Fonctionnant à la fois comme matériau d'enveloppe et générateur d'électricité, le BIPV permet simultanément un recours réduit aux combustibles fossiles et une limitation des émissions de gaz à effet de serre, tout en réalisant des économies matérielles et financières. Ces effets sont compatibles avec les objectifs de la majorité des directives énergétiques européennes relatives au bâtiment (zéro-énergie, énergie positive, etc.). Malgré les progrès technologiques et la baisse continue des coûts des cellules, les pratiques courantes n'intègrent cependant encore que très peu le BIPV. Divers obstacles liés notamment à la technologie employée, à la faible demande (induisant un faible volume de production) et au manque d'information et d'exemples convaincants de projets de rénovation, limitent l'adoption des solutions BIPV.

En intégrant le BIPV au sein du processus de conception, par l'intermédiaire d'une approche spécifique liée à des études de cas, cette thèse vise à apporter un support aux acteurs impliqués dans de tels projets, en particulier aux architectes. L'approche, se décline en quatre phases : (1) l'identification de situations archétypiques par l'analyse du parc immobilier, (2) l'analyse détaillée de cas d'étude, (3) le développement de scénarios de rénovation intégrant différentes stratégies BIPV, et (4) l'évaluation multicritère de chaque scénario. Les contributions de cette thèse sont de deux ordres. D'une part, un ensemble de stratégies de design est défini et illustré au travers de cas d'étude de bâtiments réels. Celui-ci intègre : (i) des stratégies passives visant à améliorer l'enveloppe avec des matériaux à faible énergie grise, (ii) des stratégies BIPV, faisant usage de produits photovoltaïques innovants comme nouveau matériau pour les façades et les toitures, et (iii) des stratégies actives visant à améliorer l'efficience des installations BIPV par l'adaptation des systèmes techniques (chauffage, eau chaude sanitaire et ventilation), afin d'optimiser la rentabilité des investissements et de réduire la dépendance aux subventions. D'autre part, la thèse comprend le développement d'une méthodologie d'évaluation multicritère pour comparer différents scénarios d'intervention, par une approche qualitative et quantitative. Ce processus d'évaluation permet de comparer les alternatives de design selon des critères énergétiques et économiques. Cette approche fournit aux architectes et ingénieurs des stratégies de rénovation BIPV adaptées à différentes typologies de bâtiments, objectifs spécifiques lies à la démarche architecturale et niveaux d'intervention, afin d'appuyer et d'inspirer ces acteurs sur la voie d'une contribution à un environnement construit bas carbone.

Mots clés : rénovation des bâtiments | photovoltaïque intégrée au bâtiment | design intégré | analyse multicritère | architecture durable | analyse de cycle de vie | bâtiments faibles en carbone | neutralité carbone.

Resum

Les ciutats europees del demà ja estan en gran part construïdes, ja que una gran part dels edificis actuals, caracteritzats per la seva baixa eficiència energètica, seguiran estant presents en 2050. Per tant, la renovació urbana té un paper essencial per a la transició cap a la sostenibilitat. En aquest context, els sistemes fotovoltaics integrats als edificis (BIPV) tenen el potencial de contribuir significativament en l'assoliment dels objectius d'eficiència energètica i petjada de carboni, inherents al concepte de la Societat a 2.000 watts a Suïssa. Funcionant com a material d'envoltant tèrmica i com a generador d'electricitat, els sistemes BIPV redueixen simultàniament l'ús de combustibles fòssils i limiten les emissions de gasos a efecte hivernacle, al mateix temps que aconsegueix estalvis materials i financers. Aquests efectes són compatibles amb els objectius de la majoria de les directives energètiques europees relatives als edificis (energia gairebé nul·la, energia positiva, etc.). Malgrat els avenços tecnològics i la disminució contínua dels costos de les cèl·lules fotovoltaiques, la pràctica actual encara inclou molt poc els sistemes BIPV. Diversos obstacles, com la tecnologia utilitzada, la baixa demanda (el que es tradueix en un baix volum de producció), la manca d'informació i d'exemples convincents de projectes de renovació, limiten l'adopció de solucions BIPV.

Mitjançant la integració BIPV en el procés de disseny, a través d'un enfocament específic vinculat a diversos casos d'estudi, aquesta tesi té com a objectiu donar suport als actors involucrats en aquests projectes, en particular als arquitectes. La metodologia es divideix en quatre fases: (1) la identificació de situacions arquetípiques mitjançant l'anàlisi del parc d'edificis, (2) l'anàlisi detallada dels casos d'estudi, (3) el desenvolupament d'escenaris de renovació que integrin diferents estratègies BIPV, i (4) l'avaluació multi criteri de cada escenari. Les contribucions d'aquesta tesi són de dos tipus. D'una banda, es defineix un conjunt d'estratègies de disseny que s'il·lustren a través de casos d'estudi reals. Aquestes inclouen: i) estratègies passives per millorar l'envoltant de l'edifici amb materials de baixa energia grisa, ii) estratègies BIPV, utilitzant productes fotovoltaics innovadors com a nou material per a façanes i cobertes, i iii) estratègies actives per millorar l'eficiència de les instal·lacions BIPV mitjançant l'adaptació dels sistemes tècnics (calefacció, aigua calenta sanitària i ventilació), per tal d'optimitzar la rendibilitat de les inversions i reduir la dependència de les subvencions. D'altra banda, la tesi inclou el desenvolupament d'una metodologia d'avaluació multi criteri per comparar diferents escenaris d'intervenció, utilitzant un enfocament qualitatiu i quantitatiu. Aquest procés d'avaluació permet comparar alternatives de disseny segons criteris energètics i econòmics. Aquest enfocament proporciona als arquitectes i enginyers, estratègies de renovació BIPV adaptades a diferents tipus d'edificis, objectius específics relacionats amb l'objectiu arquitectònic i nivell d'intervenció, per tal de donar suport i inspirar a aquests actors en el camí cap a la contribució a un entorn construït baix en carboni.

Paraules clau: renovació d'edificis | fotovoltaica integrada a l'edifici | disseny integrat | anàlisi multi criteri | arquitectura sostenible | anàlisi del cicle de vida | edificis amb baixes emissions de carboni | neutralitat de carboni.

Resumen

Las ciudades europeas del mañana ya están construidas en gran parte, ya que una gran parte de los edificios actuales, caracterizados por su baja eficiencia energética, seguirán estando presentes en 2050. Por lo tanto, la renovación urbana desempeña un papel esencial para la transición hacia la sostenibilidad. En este contexto, los sistemas fotovoltaicos integrados en los edificios (BIPV) tienen el potencial de contribuir significativamente en el alcance de los objetivos de eficiencia energética y huella de carbono, inherentes al concepto de la Sociedad a 2.000 vatios en Suiza. Funcionando como material de envolvente y como generador de electricidad, los BIPV reducen simultáneamente el uso de combustibles fósiles y limitan las emisiones de gases a efecto invernadero, al mismo tiempo que logra ahorros materiales y financieros. Estos efectos son compatibles con los objetivos de la mayoría de las directivas energéticas europeas relativas a los edificios (energía casi nula, energía positiva, etc.). A pesar de los avances tecnológicos y la disminución continua de los costes de las células fotovoltaicas, la práctica actual todavía incluye muy poco los BIPV. Diversos obstáculos, como la tecnología utilizada, la baja demanda (lo que se traduce en un bajo volumen de producción), la falta de información y de ejemplos convincentes de proyectos de renovación, limitan la adopción de soluciones BIPV.

Mediante la integración de BIPV en el proceso de diseño, a través de un enfoque específico vinculado a diversos casos de estudio, esta tesis tiene como objetivo apoyar a los actores involucrados en dichos proyectos, en particular a los arquitectos. El enfoque se divide en cuatro fases: (1) la identificación de situaciones arquetípicas mediante el análisis del parque de edificios, (2) el análisis detallado de los casos de estudio, (3) el desarrollo de escenarios de renovación que integren diferentes estrategias BIPV, y (4) la evaluación multicriterio de cada escenario. Las contribuciones de esta tesis son de dos tipos. Por un lado, se define un conjunto de estrategias de diseño que se ilustran a través de estudios de caso de edificios reales. Estas incluyen: i) estrategias pasivas para mejorar la envolvente del edificio con materiales de baja energía gris, ii) estrategias BIPV, utilizando productos fotovoltaicos innovadores como nuevo material para fachadas y cubiertas, y iii) estrategias activas para mejorar la eficiencia de las instalaciones BIPV mediante la adaptación de los sistemas técnicos (calefacción, agua caliente sanitaria y ventilación), con el fin de optimizar la rentabilidad de las inversiones y reducir la dependencia de las subvenciones. Por otro lado, la tesis incluye el desarrollo de una metodología de evaluación multicriterio para comparar diferentes escenarios de intervención, utilizando un enfoque cualitativo y cuantitativo. Este proceso de evaluación permite comparar alternativas de diseño según criterios energéticos y económicos. Este enfoque proporciona a arquitectos e ingenieros estrategias de renovación BIPV adaptadas a diferentes tipos de edificios, objetivos específicos relacionados con el objetivo arquitectónico y nivel de intervención, con el fin de apoyar e inspirar a estos actores en el camino hacia la contribución a un entorno construido bajo en carbono.

Palabras clave: renovación de edificios | fotovoltaica integrada en el edificio | diseño integrado | análisis multicriterio | arquitectura sostenible | análisis del ciclo de vida | edificios con bajas emisiones de carbono | neutralidad de carbono.

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1. Introduction

1.1. Context and motivation

On 4 November 2016, the Paris Agreement – a milestone in the history of environmental policy – came into force after reaching the ratification threshold of 55 Parties to the Convention. The Agreement's main objective is *"to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C."* **[UN 2015]**.

Commissioned by the Paris Agreement, a special report by the Intergovernmental Panel on Climate Change (IPCC) investigated the impacts of a 1.5°C global warming and to what this temperature increase would correspond in terms of the evolution of global greenhouse gas (GHG) emissions. They notably concluded that: *"Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems […]."* [**IPCC 2018**].

1.1.1. Greenhouse gas emissions of the building stock and reduction objectives

In light of this objective, considerable reductions in GHG emissions are required in all sectors, including the built environment in which buildings are currently responsible for 36% of GHG emissions in the European Union [**EC 2018a**]. Reducing the energy consumption and GHG emissions associated to the built environment is in fact one of the priorities of European countries, for which a reduction target of 80-95% in GHG emissions (compared to 1990) has been set for 2050 [**EC 2018a**]. The Energy Performance of Buildings Directive (EPBD) that contains the above-mentioned objectives, has also set highly-demanding performance standards for new buildings, from zero- to positive-energy buildings [**EU 2010, 2012a; Hernandez et al. 2010; EC 2012; Li et al. 2013; BPIE 2015; D'Agostino 2015**]. The existing building stock is particularly put in the spotlight in the most recent revision of the EPBD [**EC 2018a**], which stresses the importance of renovation processes, identified as a key measure to achieve the 2050 targets.

Indeed, since the cities of tomorrow are already largely built and the current replacement rate of existing buildings is low, the relevance of renovation processes as a strategy towards the sustainable development of our built environment has been widely acknowledged **[IPCC 2007; SNSF 2012; Riera Pérez et al. 2013; EU 2018]**. The IPCC affirms that, due to the slow turnover of the building stock, the largest share of carbon savings that can be achieved by 2030 is in the retrofitting of existing buildings and the replacement of inefficient equipment **[IPCC 2007]**.

Along with the global **[IPCC 2014]** and European **[EU 2018]** level initiatives to mitigate the effects of climate change, national regulations and initiatives emerged in Switzerland. As early as the 1980's, the 2'000-Watt Society concept was introduced, promoting an annual limit per person of 1 tonne of CO_2 emissions and of 2'000 W_{PE}/pers·year (expressed in mean power of total primary energy – PE) and 500 W_{NRPE}/pers·year (of non-renewable primary energy – NRPE) by 2100 [**Suisse Energie 2018a**]. An intermediate objective for 2050 is fixed at 2 tonnes of CO_2 emissions, 3'500 W_{PE}/pers·year, and 2'000 W_{NRPE}/pers·year. For reference, in 2017 these values were of 6.5 tons of CO_2 emissions and 4'710 W_{PE}/pers·year [**Suisse Energie 2018a**].

These objectives have been converted by the Swiss Society of Engineers and Architects (SIA) into targets for new and existing buildings of different types (e.g. residential, commercial), with sub-targets set for the construction, operation, and building-induced mobility domains [**SIA 2017a, 2018**]. SuisseEnergie, a federal programme that promotes energy efficiency and renewable energy through voluntary measures, has adopted and translated the 2'000-Watt Society concept and the SIA targets into various certification schemes such as the Cité de l'énergie [**Suisse Energie 2018b**] and the 2'000-Watt Site [**Suisse Energie 2018c**].

These initiatives are in line with the Swiss *"Energy Strategy 2050"* [**OFEN 2018a**], recently materialised through the latest Swiss Energy Law (LEne) [**AFCF 2018**]. This strategy plans the progressive abandonment of the use of fossil fuels and nuclear energy, the latter notably motivated by the Fukushima disaster of 2011. The first set of measures of the Energy Strategy 2050 include subsidising the cost of energy-saving building renovations and photovoltaic (PV) installations, to increase energy efficiency and promote renewable energies [**OFEN 2018a**].

1.1.2. Energy-saving renovation of the residential building stock

Renovating the building stock is thus essential for achieving the various carbon reduction objectives. Within the Swiss building sector, 66% of the existing buildings are for housing, totalling to 1.73 million residential buildings [**OFS 2016a**]. Out of those buildings, 70% (about 1.3 million buildings) were built before 1985 and have between 30 to 60 years of age. As Swiss building energy regulations began to slowly appear in the late 70s [**archiwatt 2006**], this large share of the building stock consumes significant amounts of energy and thus represent an important energy-saving potential were they to be renovated.

According to the Federal Statistical Office (*"Office fédéral de la statistique"*; OFS), interventions on existing residential buildings (e.g. transformations, extensions or demolitions) have been on the rise since 1980 [**OFS 2016a**]. However, investments continue to be made in new constructions regardless of the real demand for housing, as proven by the vacant housing rate which has risen since 1985 and is currently at 1.45%. This is especially due to the low (sometimes negative) interest rates offered by banking entities [**Suisse Energie 2018a**]. Still, in 2016, the renovation sector presented three times more investment than the new construction sector.

In Switzerland, favourable conditions in the form of economic aid make this a propitious moment to undertake such building renewal interventions. Unfortunately, in spite of these positive conditions and rising prices of non-renewable energy sources – above all fossil fuels whether due to supply-demand pressures, political issues or exponentially increasing CO_2 taxes – energy renovations occur at a too low rhythm. Indeed, although the renovation sector shows continuous increase in activity, the renovation rate of the residential building stock still does not exceed 0.8% per year [**Passer et al. 2018**].

Moreover, as is observed in common practice, most of the renovations that are carried out do not have high performance objectives. Instead, they simply aim to comply with the existing regulations [**SIA 2016a**], which are in turn not demanding enough to achieve the 2050 objectives.

1.1.3. PV as a key contributor towards the 2050 objectives

In parallel to renovating the building stock, further reductions in GHG emissions can be achieved by replacing polluting energy sources by renewable sources such as solar energy. As mentioned, increasing the use of renewable energy is also one of the objectives of the Swiss Energy Strategy 2050 [**OFEN 2018a**]. Solar energy, in particular in the form of photovoltaic electricity, represents a type of renewable source that holds significant potential in contributing to the Swiss energy transition. According to the International Energy Agency (IEA), it would be possible to cover one third of the annual Swiss electricity demand by installing photovoltaics on the available building surfaces [**IEA 2002**].

From 1990 to 2016, the number of PV installations has grown from 210 to 58'080 with an installed power of 2.1 to 1'660 MWp respectively, producing from 1.5 to 1'333 GWh/year [**OFEN 2016a**]. In terms of contribution to the global electricity production in Switzerland, the PV share has gone from 0.002% (1990) to 2.2% (2016). As can be seen in Figure 1-1, the expansion has been particularly important between 2010 and 2016, where the production has grown 13-fold.

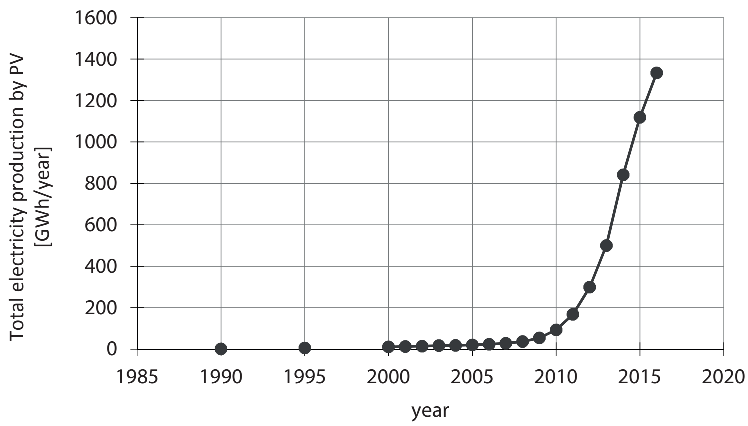


Figure 1-1. Evolution of the PV electricity production in Switzerland, from 1990 to 2016 [**OFEN 2016a**].

Worldwide, the PV sector has grown; between 2010 and 2016, the increase has been of 40% [**SolarPower Europe 2017; Fraunhofer ISE 2018**], and the sector is expected to grow exponentially over the next decades. The main factor that has allowed this spectacular development has been the constant decrease in prices during the last 25 years, going from an average cost (for a typical roof-mounted PV system) of 14'000 €/kWp in 1990 to 1'270 €/kWp in 2016, according to the Fraunhofer Institute for Solar Energy Systems (ISE) [**Fraunhofer ISE 2018**]. Likewise, improvements in manufacturing processes have not only contributed to the price drop, but also to the reduction of the environmental impact associated to the use of raw materials necessary for the production of photovoltaic panels and components. For example, the amount of material used to build PV panels based on crystalline silicon cells (mono and poly) has been reduced by 56% since 1990 [**Fraunhofer ISE 2018**].

Building-integrated renewable energy (BiRES) systems – and in particular building-integrated photovoltaic (BIPV) systems – have been identified as major mitigation strategies for carbon efficiency by the IPCC **[IPCC 2014]**. BIPV systems consist of PV modules that, in addition to producing electricity, take on the function of a specific building envelope element **[IPCC 2007]**. BIPV is a growing and diverse area of investigation, with research being conducted particularly on new product development and on the modelling, simulation, and assessment of their integration on buildings **[Frontini et al. 2012b]**.

1.1.4. Incentives and barriers to building renovation and BIPV-integration

As mentioned, the Swiss Energy Strategy 2050 provides incentives to improve energy efficiency, notably through direct subsidies and tax deductions for conducting energy-saving building renovations. Regarding solar installations, these are being promoted in Switzerland at the Federal **[AFCF 2018]**, Cantonal and Communal level **[EnDK 2014]** by: simplifications in the administrative process for roof installations, offering direct economic subsidies based on the installed power **[OFEN 2018a]**, encouraging self-consumption of on-site produced energy and sharing through micro-grids at the neighbourhood scale, and guaranteeing the possibility to inject the overproduction into the grid in accordance with the local electricity supplier (feed-in-tariff).

Even in this favourable context, both for the energy renovation of existing buildings and for the implementation of photovoltaic solar energy, these strategies remain underutilised in common practice. This is mainly due to a series of barriers and myths (or preconceptions) that block the large-scale development of these two strategies. These relate among others to technology choices, restricted knowledge of BIPV potential, conservatism, lack of information, and insufficiency of aesthetically-convincing exemplary buildings **[Heinstein et al. 2013]**. Combined with the small volume of production of BIPV products, induced by a low demand for such products, these barriers tend to increase costs and hinder the acceptability of BIPV solutions.

In the renovation of buildings, the main obstacle is related to the financial aspects of the interventions, since the profitability objectives of the building's owner are often set too high. Specifically, if the internal rate of return (IRR) does not exceed 2.5-3%, owners are unlikely to undertake action, or they will opt for the option of doing as little as possible: simple maintenance tasks to replace obsolete or damaged elements or renovating the building envelope to reach the minimum legal requirements **[SIA 2016b]**, with the ultimate goal of maintaining the value of the property. Even though this type of minimal renovation has a non-negligible impact on the reduction of energy consumption and CO_2 emissions, it is not enough to achieve the 2050 objectives **[Roger W et al. 2007; OFEN 2018a]**.

One of the main actors involved in the decision-making process in building renovation projects, and who have a key role in the development of energy renovations integrating photovoltaic energy, are architects. The architect is the actor who, when consulted, can propose alternative renovation strategies to the owner of the building. However, nowadays, architects generally do not take into account the possibility of incorporating BIPV strategies into their designs, mainly due to a limited knowledge of the available products and their multiple integration possibilities **[Farkas et al. 2012]**. In addition, PV technology and more precisely its installation is considered as belonging to the building technique and thus, by default, falling into the domain of engineers [**Palm et al. 2018**]. Indeed, PV are seen as elements that are added a posteriori on a building, using panels with an undesirable appearance from a design point of view. This can be true in cases where systems are implemented on buildings according to the Building-Added photovoltaic (BAPV) concept, which consists in simply using the surfaces offered by existing buildings as physical support for the installation.

However, experts have long emphasised that it is more effective (technically and economically) to integrate photovoltaic systems at the time of construction or renovation of a building [**Reijenga et al. 2012**]. This is increasingly being done for new non-residential buildings (e.g. office and commercial buildings), where BIPV is more widespread. This is mainly because BIPV integration is more evident in new than existing buildings, mainly due to the geometric or compositional freedom, as shown by recent examples that can be found in [**Swissenergy et al. 2018**]. In the renovation of residential buildings, the use of BIPV is still marginal. This lack of convincing built examples represents an important barrier for a wider integration of PV, since reference consultation is an important step of the architectural creative process. Moreover, BIPV is still mainly limited to rooftop integration or to isolated demonstration projects [**Ballif et al. 2018**].

However, thanks to the products that exist on the market and the increase in the possibilities of customisation in terms of size and appearance, this situation should be able to change. To achieve this transition, architects need to better know how photovoltaic energy can be integrated into renovation processes.

1.1.5. Synthesis – Overcoming barriers through an architectural design approach

With over 1 million residential buildings ready to be renovated in Switzerland and the potential for the deployment of photovoltaic energy corresponding to covering up to 35% of the total Swiss energy demand [**IEA 2002**], the synergies between renovation processes and building-integrated photovoltaic systems are evident.

When PV is used in a non-integrated way, either from a construction or design point of view, the acceptability of renovation projects with PV elements remains low [**Hirschl 2005**]. To avoid oppositions to the project, the current approach is thus to use surfaces that are the least visible from public spaces, typically flat- and some inclined-roof surfaces [**Florio 2018; Munari Probst et al. 2018**]. Simply using these less visible surfaces makes it difficult to achieve the objectives set by the Energy Strategy 2050. We argue that there is a need to foster the synergies through an integrated-design strategy to increase the acceptability of active renovation projects (i.e. including BIPV systems).

From these observations, it can be seen that the architect is a key stakeholder in promoting this deployment. Current barriers that explain the limited motivation of architects are mainly of economic-technology nature, as well as aesthetical reasons particularly for non-integrated elements.

As such, this thesis focuses on linking the energy renovation processes of existing residential buildings and the integration of photovoltaic energy within this process. It aims to help overcome the barriers that currently prevent BIPV from expanding, ultimately contributing to improving the built environment. The objectives and contributions of this research are further described below.

1.2. Objectives

This thesis anticipates the evolution of the norms towards the decarbonisation of the built environment, which will bring building designers to be confronted with increasing frequency to the challenges of designing retrofitted active building envelopes, both for roofs (a sector already well-developed) and for façades, and for any type of building.

Anchored in the Swiss context, the research thus aims to provide designers and stakeholders involved in the renovation process, including public authorities, with the relevant information, an adequate method, and appropriate examples to facilitate widespread BIPV applications, and in that way assist in reaching compliance with the Energy Strategy 2050.

Adopting the point of view of the architect, the main goal is to help overcome the identified obstacles by developing concrete strategies for a better integration of BIPV systems in the design process of urban and building renewal projects. To do so, an underlying objective is to define what is the most adequate way to integrate PV elements into the envelope of buildings in renovation projects.

Through our approach and methodology introduced below and further described in Chapter 2, the outcome of this research can be seen as a decision-support package that offers not only worked-out exploratory case studies for a given set of archetypical buildings – forming *a catalogue of innovative and adapted renovation examples* to accelerate the transfer to practice – but also the underlying workflow for developing and assessing such scenarios for any given context (e.g. defined by the climate, context, building features, etc.). The results shall also highlight, to stakeholders of the BIPV industry, the significant market potential regarding the residential building stock and the type of products that could help architects design high-quality façades more easily.

1.3. Thesis structure

Chapter 1 has laid out the general **context** and **motivation** for conducting this research, highlighting the two main topics addressed and brought together: the renovation of the residential building stock and the integration of photovoltaic energy.

Chapter 2 exposes the **research questions, approach** and **objectives** before detailing the **methodology** developed to answer the question and fulfil the objectives. This methodology unfolds in four main phases, here introduced and positioned with respect to the manuscript's structure.

Chapter 3 describes the **state of the art** and **research framework** related to the different fields relevant to all phases of the methodology.

The core of this research – the four phases of the methodology – is covered in Chapters 4 to 7.

Chapter 4 presents **Phase 1** of the methodology, consisting in the urban study of the existing residential building stock of the city of Neuchâtel, taken as a case study city, representative of a middle-sized city of the Swiss plateau where most of the population is concentrated. As urban renewal processes involve carrying out interventions on a wide variety of existing buildings found in urbanised areas, this study allows gathering a structured understanding of this diversity of the building stock and linking urban and building scales through the identification of residential building archetypal situations.

Chapter 5 describes **Phase 2** consisting in the selection and description of five real buildings taken as case studies, each corresponding to one of the representative building categories previously defined (archetypes). Each case study building is studied to draw a clear picture of its current status.

Chapter 6 details **Phase 3** where a set of design strategies in the form of renovation scenarios are defined and implemented (applied) on each case study. Through this project realisation process, we investigate the ways in which BIPV can be integrated, both literally/physically as a functional building element, as well as conceptually within the renovation design process.

Chapter 7 presents **Phase 4** in which a qualitative and quantitative assessment of the different scenarios for each archetype is conducted, in iteration with the design phase (Phase 3). This multi-criteria evaluation includes: 1) a qualitative assessment of the scenarios through a workshop held among an interdisciplinary group of experts active in the renovation domain and the BIPV industry sector, to ensure the acceptability of the projects; 2) a quantitative assessment with a set of indicators including the energy, environmental and economic aspects and taking into account the whole life-cycle of the building renovation process.

Chapter 8 exposes the **conclusions** and **outlook** from this research.

2. Research question and methodology

This section introduces the main **research question**, and the hypothesis underlying this doctoral work and discusses key elements of the **research approach** before presenting the **methodology and research phases**.

2.1. Research question

In accordance with the international commitments related to the Paris Agreement, the core objectives of the Swiss energy turnaround, which are the withdrawal from nuclear energy and the reduction of GHG emissions, open up the path for an increase in the share of energy from renewable sources, notably through photovoltaic installations. In addition, in the built environment, sustainability issues naturally point to the need to address the untapped energy efficiency potential in the renovation of the building stock.

The direct application of PV in architecture has however been met by some restraint from the different parties concerned, a barrier that the BIPV concept attemps to overcome. Currently mainly applied in the design of new buildings, our initial observation is that BIPV in renovation is not well defined today. BIPV is considered as a construction material that produces electricity. While this remains true in the renovation context, this thesis is motivated by the quest to further define the role BIPV can have in building renovation, with the ***hypothesis that BIPV can be simultanesously considered as one of the significant contributions towards low-carbon buildings and as integral part of the architectural design strategies in urban renewal processes***. If adequately adopted by designers, BIPV could help stimulate the sustainable renovation of buildings, contributing to achieving the 2050 energy objectives while ensuring cost-effectiveness and comparable architectural quality as if any other construction material was used. This hypothesis leads us to defining the following **research question**:

What role can BIPV have in the architectural design processes of residential building renovation ?

To provide answers to the research question, a methodology is developed, bridging the urban and building scales as well as the design, construction and technological aspects. Prior to describing this methodology, the next section introduces core elements of the research approach, which consists in addressing the above issues through the lens of the architecture discipline. Considering architects as key actors to achieve the 2050 objectives in terms of energy efficiency of the residential building stock, this thesis aims to bring about a paradigm shift around BIPV, encouraging architects to seize new opportunites and to discover how this technology can be integrated from the design process by showing, through case studies on real existing buildings, what the result can be from an architectural language perspective as well as in energy, environmental and economic terms.

2.2. Core elements of the approach

2.2.1. Design-driven research approach

The quality of an architectural project is defined through a set of parameters that must be considered simultaneously through a multidisciplinary approach. Capturing this set of parameters requires a research methodology linked to the operational framework of the process under study, in this case the renovation process. That is, the methodology must be based on the complete process of a project and on the study of the multiple scenarios made possible when projecting a design solution onto this project. In this sense, the architecture project can become a true investigation tool.

Design-driven research, based on the definition of general objectives applied to specific case studies, is an approach that is increasingly used in architectural research [**Fumeaux 2016**]. It allows exploring different scenarios and offers a palette of possible solutions in which architects can find the inspiration / references necessary to advance their own projects [**Julien et al. 1975**].

This practical approach to architectural research relates to what Findeli defines as *"research through design"* or *"project-grounded research"*, i.e. a *"type of active research, located and engaged in the field of a design project"* **[Findeli 2005]** (translated from French, own translation). Findeli adds that *"to think just in design, we have to think 'in action' and not in an ivory tower"* (ibid).

This approach also relates to that of conducting applied research, which, in the field of BIPV, has been identified as a necessity to accelerate the integration of this technology on buildings by the IEA [**Eder et al. 2017**].

This research adopts a design-driven approach by developing architectural renovation design strategies and projecting them onto real buildings, taken as archetypical case studies.

2.2.2. BIPV as a new architectural material

Instead of considering BIPV as a technical constraint for designers, this thesis proposes a new approach based on the integration of BIPV solutions as a new *"raw material"* for architectural renewal projects [**Aiulfi et al. 2010; Rey 2014**], by prioritising architectural quality and dialogue with the built environment.

It aims at identifying which construction elements can be substituted by BIPV components giving the most appropriate response to the requirements of the overall design of the renovation, fulfilling the building envelope requirements (e.g. water and air tightness, mechanical resistance, etc.), while generating electricity on site from a renewable energy source.

To move from the more common application of PV elements on building surfaces (mainly roof) towards the integration of such elements within the building envelope, the consideration for BIPV must begin at the early design stage of the renovation process. This is here done by anchoring our approach within the realm of the architectural design process and integrating the BIPV concept within this process.

2.2.3. Simulation as a design tool

The concept of integrated-design on which this thesis is based embraces the idea that the integration of BIPV must be taken into account from the initial phases of conception and following an iterative process combining design and energy simulations, allowing to verify the impact of the design-decisions on the efficiency objectives.

As **[Peters et al. 2018]** state: *"Simulations is what allows architects to 'work out the consequences' of their innovations"*. Although the realm of simulation has traditionally been considered as part of the work of the engineer, the boundaries between disciplines are gradually shifting and overlapping, as a growing number of architects are trained and are starting to use computer-based simulation tools within their practice **[Alsaadani et al. 2012; Reinhart et al. 2015; Peters et al. 2018]**. For Khan and Marsh, simulation is to become a design tool, an indispensable element of any design process **[Peters et al. 2018]**.

Simulation allows us to immediately get feedback on the expected performance of each design scenario in terms of different quantities not only related to the predicted energy consumption, but also to the indoor thermal and visual comfort. It contributes to the multidisciplinarity of this work and plays an important role in the multi-criteria assessment of the proposals.

2.2.4. Multi-criteria sustainability assessment

As BIPV is a multi-functional building element, **[Zanetti et al. 2017]** highlights the necessity to conduct a multi-criteria assessment to demonstrate and compare the benefits of using this new *"building material"*.

Our approach involves the development of a multi-criteria evaluation method to assess and compare the different scenarios through quantitative environmental and economic indicators, as well as from a socio-cultural perspective through qualitative feedback gathered from stakeholders. Through this multi-criteria assessment of the sustainability of the scenarios, information is collected on the impact of the design choices made in the development of the renovation strategies.

The qualitative evaluation has a central role in this thesis as it allows validating the different design proposals as acceptable project solutions for their realisation. The objective of conducting this qualitative evaluation is not to define or identify the best possible scenario, but to ensure that a series of valid scenarios are offered to respond to the design objectives previously set. This thesis indeed aims to demonstrate that through design, it is possible to integrate BIPV towards its wider approval and acceptance.

The quantitative evaluation highlights the influence of the architectural design decisions on the final performance with respect to the building consumption profile, helping us to move towards a more precise definition of what we mean by implementation of BIPV systems into building renewal design processes.

In order to overcome the low acceptance barrier, it is thus important to reject the idea that a building, if it has a higher energy performance, is allowed to be less acceptable from a design point of view. As such, we do not propose to convert the qualitative assessment into a quantifiable indicator towards computing a unique aggregated, average, or weighted performance of the proposals. Doing so could result in that a project that receives a high rating for its energy efficiency be evaluated as acceptable in spite of having a low architectural quality.

The above concepts are fundamental to the research methodology developed to answer our research question, described in the next section.

2.3. Methodology and research phases

The methodology involves four main phases, illustrated in Figure 2-1: 1) selection of archetypal residential buildings; 2) detailed analysis of each building; 3) development, for each archetype, of four architectural renewal scenarios embodying different levels of intervention and including BIPV strategies; 4) multi-criteria assessment of the scenarios.

While the full development and application of the methodology can be found in Chapters 4 to 7, each phase is briefly described below.

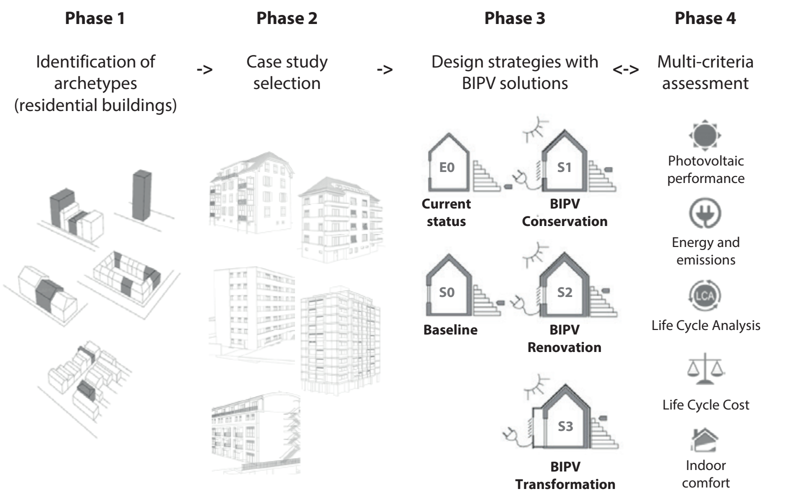


Figure 2-1. Diagram of the proposed research methodology.

2.3.1. Phase 1: Identification of archetypical situations

In this first phase (Chapter 4), a representation of the diversity of the built environment is done by identifying the most common building typologies in the Swiss context, based on the urban and architectural analysis of a representative middle-size city of the Swiss Plateau (Neuchâtel).

An analysis of the existing residential buildings is done, primarily based on the main construction periods in Switzerland until 2005, but also on a typological study including parameters such as the urban context, the potential of exposed surfaces, the architectural quality (level of protection) and the type of ownership. Different data sources are used, including the current master plan, aerial images, information from registration of the land owner, and statistical data from the construction sector using a Geographic Information System (GIS).

This analysis leads to the definition of five archetypical situations.

2.3.2. Phase 2: Selection of real representative buildings

In Phase 2 (Chapter 5), a selection of real buildings representative of each archetypal definition made in Phase 1 is done. The current status (identified as E0-Current status) of these case study buildings is documented and analysed, including the thermal envelope's construction characteristics, the systems in place, etc.

2.3.3. Phase 3: Development and application of design scenarios with BIPV solutions

In Phase 3 (Chapter 6), four renovation design scenarios are developed and subsequently applied to each case study building. These scenarios involve different levels of intervention, defined primarily according to architectural objectives, which are in turn refined based on energy efficiency targets. The set of scenarios include a baseline proposal without any BIPV integration, and three gradually more consequential scenarios that make an increasing use of BIPV elements.

These general design concepts are implemented taking into account the specific characteristics of each building. Consequently, the strategies are adapted to each case study to provide the most adequate means for achieving the design objectives.

The proposed scenarios are:

S0-Baseline scenario, a reference scenario aiming to achieving at least the current legal requirements defined by SIA 380/1:2016 [**SIA 2016a**], in accordance with current practice, through the implementation of passive strategies only (i.e. improving the efficiency of the envelope), and without any BIPV strategy.

S1-Conservation (BIPV), a scenario aiming at maintaining the substance / expression of the building when possible (considering current practice), while improving its energy performance by replacing defective elements with more performing ones (e.g. windows, wall internal insulation), to reach at least the current legal requirements [**SIA 2016a**]. The interventions include the integration of BIPV elements.

S2-Renovation (BIPV), a scenario corresponding to maintaining the general expressive lines of the building while reaching high energy performance (deep retrofit including placing photovoltaic elements wherever possible). This scenario offers the possibility of exploring the limits of a mimicry approach, trying to imitate the materiality of the existing building using active (BIPV) elements. In terms of energy performance objectives, we consider as reference at least the requirements fixed by the Swiss Minergie® label [**Minergie 2018**].

S3-Transformation (BIPV), this final scenario proposes a global strategy corresponding to maximising the photovoltaic contribution towards reaching the best energy performance possible with aesthetic and formal coherence of the whole building, but by allowing the image of the building to be changed in a more obvious way, in order to achieve at least the objectives of the 2'000-Watt Society [**SIA 2017a**] according to the Energy strategy 2050 [**OFEN 2018a**]. The results of this scenario should show the energy performance improvement potential for each type of building and the feasibility of achieving the 2'000-Watt Society concept targets.

This design phase consists in an iterative procedure between design at the construction level and energy simulation in order to continuously verify the final performance of each design proposition.

2.3.4. Phase 4: Multi-criteria assessment

In this final phase (Chapter 7), a multi-criteria assessment of the design scenarios integrating both qualitative and quantitative aspects is conducted. The qualitative part of this assessment consists in evaluating the acceptance of the proposals through focus groups with experts involved in the renovation and PV practice. The quantitative part is conducted through dynamic simulations, based on Life-Cycle Analysis (LCA) and Cost (LCC) for a 60-year lifespan, and taking into account energy consumption, GHG emissions, on-site PV generation, environmental impact of materials including BIPV elements, cost-effectiveness and indoor comfort (overheating risk and daylighting potential).

Through an iterative process between this assessment phase and the design implementation phase (Phase 3), the different designs are refined in an integrated way to ensure their architectural quality.

3. Research framework

This chapter presents the research framework of this thesis, including the review of the literature on renovation projects and the integration of photovoltaics, with a focus on the Swiss context. The literature review is organised in three main parts: building renewal processes (Section 3.1), photovoltaics in architecture (Section 3.2) and assessment methods and tools (Section 3.3). The chapter concludes with the thesis' contributions with respect to the state of the art (Section 3.4).

3.1. Building renewal processes

3.1.1. Renovation of the building stock

Urban renewal is typically considered as being in line with sustainable development, both concepts targeting similar spatial and temporal scales as well as social, economic, and environmental aspects of the built environment [**SNSF 2012; Riera Pérez et al. 2013; Zheng et al. 2014**]. According to [**Power 2008**], energy refurbishment interventions make sense in terms of *"time, cost, community impact, prevention of sprawl, reuse of existing infrastructure and protection of existing communities"*, and *"can lead to a reduced energy use in buildings in both the short and the long term"*. In Europe, the energy saving potential achievable through building envelope improvements is estimated to be of 50-75% by 2050 with respect to 1990 [**IEA 2013**].

The residential sector in particular has been identified as a key sector to tackle, towards improving the built environment and mitigating climate change effects [**Filippidou et al. 2016; EC 2018a; Housing Europe 2018**]. In Switzerland, this sector represents around 70% of the total building stock, composed also of tertiary (20%) and industrial (10%) buildings [**OFEN 2014**]. Out of these 1.73 million residential buildings, 1.30 million were built before 1985 and should thus be renovated in order to achieve the 2050 objectives of the Energy Strategy [**Prognos AG 2012; OFEN 2014; OFS 2016a**]. Indeed, as shown in Table 3-1, these buildings require large amounts of energy to ensure minimum indoor thermal comfort, especially those built in the 60-70's. In addition, based on a study by [**Jochem et al. 2004**] over Swiss residential buildings, retrofits can have on the long term an impact that is half the impact of a standard demolition and reconstruction.

Table 3-1. Mean final energy needs for heating and domestic hot water according to different construction periods in Switzerland. Values are expressed in kWh/m^2·year [**Jochem et al. 2004; EnDK 2018a**].

	Construction period						
	1920	1950	1970	1980	1990	2000	2010
Heating needs	200	210	220	170	150	100	50

Yet, the current annual rate of energy efficiency renovations is very low, with estimates of 0.6% in 2014 [**Jad 2014**] and 0.8% in 2018 [**Passer et al. 2018**]. These values are much lower than the 2-3% estimated to be necessary to achieve the 2050 objectives of the Energy Strategy [**Boermans et al. 2012; Prognos AG 2012**]. These estimates correspond to conducting deep renovations (as opposed to superficial or shallow interventions). Such deep renovations require a holistic strategy including complementary measures among: 1) passive interventions to reduce the energy demand of the building (for heating and cooling), i.e. through envelope improvements such as changing the windows, 2) the replacement of inefficient HVAC systems to reduce the final energy consumption and possibly move to a cleaner energy source (e.g. fossil fuel to biomass), and 3) the integration of renewable energy systems to produce cleaner energy on-site from renewable sources.

It has been demonstrated that high energy savings can be reached by combining different types of interventions. For instance, according to [**IEA 2013; Shnapp et al. 2013**], a deep renovation can yield a 50-75% saving, whereas only 15-30% will be reached through lighter renovations corresponding to current practice.

To quantify the energy saving potential and reach numbers such as the above requires studying or modelling the existing building stock and possibly, depending on the purpose, making projections about its evolution over time. Different approaches exist to do so, falling somewhere between the two opposite scales of analysis: 1) urban scale using statistical data to show the potential energy savings from the number of buildings ready to be renovated [**Laure et al. 2008; Akbari et al. 2012; Suisse Energie et al. 2012; Boeck et al. 2013; Geier et al. 2014**], typically destined to public institutions (to promote renewal processes); and 2) specific renovation projects at the building and detailed construction level, based on case studies on which strategies are applied to show a catalogue of solutions which can serve as references in architectural practice [**LESBAT 2011; Beccali et al. 2013; López et al. 2014**]. Those building-level cases can then be extrapolated following a scaling-up (or bottom-up) approach in order to evaluate the saving potential of the whole building stock [**Jad 2014**]. To ensure the relevance and appropriateness of scaling-up building-level results, it is important that the building case studies be representative of the building stock. This requires analysing the building stock prior to defining the case studies. To do so, a common method is to classify the building stock using 'reference buildings' that are based on real buildings in a given context [**Dascalaki et al. 2011; Ballarini et al. 2014; Corrado et al. 2014; Aguacil et al. 2017**]. This method is notably used in the Typology Approach for Building Stock Energy Assessment (TABULA) project [**Intelligent Energy Europe 2016**], aiming at providing a harmonised database of existing buildings at the European level. Another approach consists in defining 'building typologies' from statistically relevant parameters identified from large datasets [**Schwehr et al. 2011; Fabbri et al. 2014; Pikas et al. 2015; Pombo et al. 2016**]. Each typology corresponds to a building having the same set of parameters, which can include the period of construction and other features relevant to the study's purpose. Also statistics-based is the concept of 'archetype', a theoretical model that represents a building typology [**Oliveira Panão et al. 2013**]. This model can be evaluated and the results scaled-up to represent the portion of the building stock associated to the archetype [**Parekh 2005; Swan et al. 2009**].

Using a model that classifies the building stock according to usage (residential or non-residential) and takes as inputs data on the country, the climate, the building features (e.g. size, age, insulation level) and the energy sources (e.g. costs), [**Boermans et al. 2012**] compared the maximum savings in terms of heating energy consumption that could be achieved when applying three renovation scenarios on the building stock of northern EU countries. Each scenario combined different levels of passive, system-related and renewable energy strategies: 1) shallow renovation (passive strategies only) with low use of renewable energy, 2) shallow renovation (passive strategies and HVAC and ventilation system improvement) with high use of renewable energy, and 3) deep renovation (passive strategies, HVAC system replacement by fossil-fuel-free system and ventilation system improvement) with high use of renewable energy. Based on hypothetical renovation rates of 3% for scenario 1) and 2.3% for scenarios 2) and 3), they estimated savings of 32%, 58% and 80% respectively.

In a study conducted by the French Agency for the Environment and Energy Management **[ADEME 2012]**, 300 high-performance new and retrofitted buildings complying with the low-energy consumption (BBC) or positive-energy buildings (BPOS) standard were analysed. Among the renovated buildings, a majority of involved strategies combine envelope (e.g. insulation and air tightness increase) and HVAC system improvements (for domestic hot water, heating and ventilation).

Despite the fact that deeper renovations mean higher savings, and in addition to the low renovation rate mentioned above, current practice is dominated by shallow renovations (only passive strategies) **[Boermans et al. 2012; Schwab et al. 2016]**. In the framework of the Advanced Energy-Efficient Renovation of Buildings research project, the Competence Centre of Energy and Mobility (CCEM) **[CCEM 2012a]** found annual renovation rates per construction elements to be of 3-6% for windows, 0.4-1.8% for façades, 1-2.8% for sloped roofs, 1.8-4.2% for flat roofs, and 0.3-2% for basement ceilings. The superior rate observed for window replacement notably demonstrates the higher occurrence of this type of intervention. It also shows that, if instead of only changing the windows a deep renovation was conducted every time, the rate required to achieve the 2050 objectives (of 2-3%) could be surpassed.

In that same study by the CCEM, an economic analysis of investment decisions for energy efficiency renovations of multi-family buildings showed that renovation typically starts after 20 years, in general with a light renovation (such as window replacement), and after 30-40 years for more in-depth interventions. Given that the average age of Swiss dwellings is of 45 years **[ESN 2009]**, deep renovations are in order.

While **[Jad 2014]** has identified the construction period of a building as the main indicator of the probability of it being renovated, the CCEM distinguishes between two main categories of influential factors **[CCEM 2012a]**: building features, such as building size and construction period (with the highest renovation rate detected for buildings dating from 1946-1970), and socio-economic factors such as age, gender or the profession of the owner, and the average rental prices in the neighbourhood/city/canton. In general, for multi-family housing with rented apartments (which represents most of the Swiss residential building stock), the most important reasons to start a renovation process have until now been: 1) to maintain the value of the building, 2) to repair damages due to the end-of-life of building components, 3) to minimise the impact of rapidly rising energy prices, especially fossil fuels, and 4) environment and climate protection reasons **[CCEM 2012a]**.

In Switzerland, the current requirements for renovation allow up to 50% more heating energy demand compared to the limit for new buildings (SIA 380/1:2016 **[SIA 2016a]**). Due mainly to economic reasons and lack of awareness about the benefits of doing a deep renovation to improve the energy efficiency of the building, the most common renovation strategy is limited to complying with the current legal requirements, consisting in a very light renovation (e.g. replacing damaged elements, windows, increasing roof insulation to reach the minimum required) **[Giebeler et al. 2011; Schalcher et al. 2011]**. This is notably the approach put forward in the eREN research project, where renovation strategies using real buildings in Switzerland were proposed **[Schwab et al. 2016]**. Their strategies follow a conservation approach to minimise the visual impact of the interventions, and exclude the definition of architectural design objectives. Moreover, the proposed renovation solutions do not guarantee achieving the current legal requirements in terms of energy demand. Some scenarios comply while others do not; there is no willingness to show architects how they should do to reach the minimum efficiency levels in order to reach the 2050 objectives. Although these examples present detailed renovation case studies, they do not go beyond current practice and are still far from proposing holistic solutions for long-term energy objectives or architectural outcomes. They also do not raise the question of renewable energy integration, a topic further addressed in the next section.

In general, the objective of this kind of light renovation is to invest as minimum as possible in order to obtain the shortest payback time. In [**Schwab et al. 2016**], it is highlighted that it is difficult to justify the cost-effectiveness of a light renovation by comparing the payback time to the lifetime of construction elements defined in SIA 480:2004 [**SIA 2016c**]. Based on results obtained for their case studies, they found that one of the most important costs in improving the energy-performance of a façade is the replacements of windows, but its impact on the reduction of energy consumption is limited if no interventions are conducted on the opaque parts of the façade as well. As mentioned, this type of renovation remains the most common in the daily practice even though it is not economically profitable at mid-term **[Schwab et al. 2016]**. There thus appears to be a lack of studies investigating the economic implications of renovation interventions through a life-cycle cost (LCC) approach, and in particular the cost-effectiveness of deeper renovations.

The same can be said regarding life-cycle assessment (LCA) within renovation projects. There is currently a lack of life-cycle vision when it comes to evaluating the energy and GHG emissions of buildings. Indeed, both the European EPBD's zero- to positive-energy building requirements **[EU 2012a]** and the Swiss SIA legal requirements [**SIA 2016b**] only consider the operational phase of a building (the latter in particular the heating energy demand), whereas 2'000-Watt Society objectives include all phases and domains, i.e. construction (embodied energy and related emissions of materials and systems), operation, and building-induced mobility. This shift towards a more holistic view of the building's life-cycle is gaining interest in the literature **[Ibn-Mohammed et al. 2013; Giordano et al. 2017; Brambilla et al. 2018; Malmqvist et al. 2018; Palm et al. 2018]**. In the last years, the number of articles on LCA has gone from 88 in 2011 to 264 in 2015 [**Anand et al. 2017**].

Moreover, while the operational phase of a building has received more attention due to its larger weight in the energy and emissions balance, the share attributed to the construction phase is starting to become more apparent. This is caused by major progress in the energy efficiency of building envelopes and systems that have led to a gradual decrease in the operational energy and emissions **[Malmqvist et al. 2018; Palm et al. 2018]**. This energy efficiency improvement partly comes from stricter regulations regarding the thermal transmittance (U-value) of opaque and glazed façade surfaces, which often require using more material (e.g. thicker insulation) [**Ibn-Mohammed et al. 2013; Giordano et al. 2017**]. This in turn amplifies the weight of the embodied impact of materials.

To conduct more in-depth renovations with an awareness for the ecological characteristics and embodied impacts of materials, several studies show the growing interest for using prefabricated elements integrating a more holistic vision of the project. The study conducted by Schwehr *et al.* [**Schwehr et al. 2011]** presents 13 worldwide case studies, including two Swiss renovated buildings, involving prefabricated façade elements. Another international project conducted by the IEA about renovation with large prefabricated elements highlights the benefits of this strategy, such as providing the possibility for room extensions and reducing technical compromises [**Zimmermann 2012**]. [**ADEME 2013**] also proposes industrialised façade systems for renovation projects, using a steel and timber construction named CRIBA to help reduce the environmental impact of the construction phase and increase the quality of the envelope component. For residential buildings, the EnergieSprong concept, developed in the Netherlands and applied within Europe and North America, proposes a complete prefabricated building envelope that is added on the existing surfaces [**Energiesprong Foundation 2018**]. This refurbishment concept is based on an Energy Services Performance Contracting, with a 30-year warrantee over indoor climate and energy performance. Retrofit modules for façades are increasingly penetrating the market in Switzerland [**CCEM 2012a**]. Examples include prefabricated construction elements proposed by [**Stahlton Bauteile AG 2018**] that aim to reduce the execution time and increase the quality of the envelope renovation. Examples of renovated buildings integrating prefabricated elements can notably be found in [**LESBAT 2011**].

3.1.2. Barriers and opportunities

Economic barriers and opportunities

One of the most important barriers to renovation projects is related to financial aspects and in particular to uncertainty in the cost-effectiveness or profitability that can be expected by the owner [**Jad 2014**]. An economic parameter that is often used and that influences decisions regarding a renovation project is the Internal Rate of Return (IRR). The IRR allows to compare the profitability of a project to an alternative investment [**SIA 2016c**]. A classic example of an alternative investment is to place money in a savings fund with an expected interest rate, typically considered to be between 3-5% [**Mattle et al. 2011**].

However, the current interest rates of investment funds are less than 1%, depending on the bank and the level of risk associated with the investment product [**bonus.ch 2018**]. Given that investors tend to have relatively high expectations, the currently low interest rate makes investments in the real estate sector (of new buildings) much more attractive.

The current trend indeed shows that, by default, investors will opt for the construction of new buildings [**RTS 2018a**], but the reality is that the ratio of vacant housing has not stopped growing in Switzerland since 2010. In 2018, this ratio exceeds 2% in some areas of the country, representing an increase of 15% with respect to 2016 [**OFS 2017**]. Renovation projects offer a very interesting alternative to these investors, but as highlighted in [**Jad 2014**], it is more difficult to trigger a renovation process if the expected IRR is more than 4%, whereas it will be easier when the expected IRR is less than 2%. Another barrier comes from the current rental law [**CFS 2018a**], which limits the increase of rental prices following a renovation to protect the tenants from disproportionate rent increase. Such abuses could occur if the owner sets a level of profitability that is too high.

A majority of multi-family buildings in Switzerland belong to a unique owner and are composed of rental flats [**Palm et al. 2018**]. The types of owners are mainly pension funds, municipalities, and private investors. The fact that the owner of the building does not reside in the building itself is one of the main barriers to starting a renovation process, because they do not directly benefit from the induced energy savings; only the tenants see how the charges (related to heating needs) of their rent decrease. According to **[Jad 2014]**, this decrease could reach -45% of the energy charges, therefore leading to more attractive monthly rents. Unfortunately, owners and investors do not perceive the situation from this angle.

To better understand the problem, it is worth delving a little deeper into the composition of the net rent (to be paid by the tenant). This net rent is composed of gross rent plus charges. The charges include the energy bill for heating and for domestic hot water. As in Switzerland most of the residential buildings for rent have a centralised heating installation, the owner estimates the energy bill and defines the monthly charges accordingly. At the end of the year, the amounts paid (normally higher than the actual consumption) are balanced. At the moment that an energy renovation is carried out, the loads derived from the heating expenses are automatically reduced and the net rent is lowered, the tenant consequently benefiting from a reduction. The problem is that owners must somehow be able to monetise their investment and for the moment, this is done by increasing the gross rent. Yet, as seen, this increase is limited by the rental law, which only allows owners/investors to pass a part of the investment cost on to the rents in order to recover the investment. The part that can be passed on includes cost of strategies that offer an added value to the tenant (i.e. improving indoor comfort, increasing the useful area), and cost of strategies that improve the energy efficiency of the building (e.g. by increasing insulation) **[CFS 2018a]**. Despite these rather clear conditions, this repartition of costs remains complex. For example, if an existing window is replaced by a more efficient one, only the cost of the improvement in efficiency can be attributed to the rent, the rest is considered maintenance work for which the owner is responsible (however, these can benefit from a tax reduction). To address such ambiguities, the rental law offers the possibility of making a simplified calculation of the amount to be passed on to the rents, which generally corresponds to 50-70% of the total investment related to energy improvement interventions **[AFCS 2017; CFS 2018a]**. In addition, the law only allows a return to the owner based on the reference mortgage index (currently 1.5%) plus 0.5%, i.e. 2%. With these margins of profitability, the majority of owners hardly decide to invest because they do not directly see the benefits. New models, for instance in terms of costs and benefits repartition between owners and tenants, could help to overcome this barrier and the financial risk perceived by owners.

In general, energy performance goals are often addressed after the economic considerations. In most cases, decisions are made based on a short-term horizon, with the goal of reaching a payback time of about 6 years **[Palm et al. 2018]**. With this extremely short investment horizon, only active strategies (i.e. replacement of HVAC system) can be considered, thus limiting the energy savings to no more than 20-30% **[Palm et al. 2018]**. In addition, the building will continue to be subjected to the energy price fluctuations and uncertainties. Resorting only to active strategies also carries the risk of missing out on the opportunity to reduce the size of the HVAC system. It is therefore necessary to plan long-term renovation strategies to avoid overlooking future energy savings opportunities.

Uncertainty-related barriers

In addition to uncertainties related to the financial savings and their dependence on energy prices, another uncertain factor is related to the performance gap **[Palm et al. 2018]**. This performance gap corresponds to the difference between the estimated (or predicted, through calculation/simulation) and actual energy savings (i.e. measured once the intervention has been carried out). Depending on the building, this difference can reach 200% [**Jad 2014]** and be caused by technical reasons (e.g. misplacement of insulation) and occupant behaviour (e.g. opening windows when the outdoor air is cooler than the interior temperature and the heating system is running). For instance, the gap related to a purely technical error or to simplifications in the calculation, for instance not accounting for thermal bridges, can lead to differences between the estimated and measured U-value ranging from -14% to 170%, according to a study by [**Schwab et al. 2016**]. In that same study, differences between -32% and 17% are observed for the heating needs, with all possible causes being more difficult to pinpoint. This performance gap serves to emphasise the need to use real consumption data to verify energy modelling simulation results during the design process [**Jad 2014**].

Barriers among decision-makers

Within the whole decision process, it is important to highlight the important role of architects, engineers, consultants and construction companies, because the majority of owners base their decisions on the assessment provided by this group of experts [**CCEM 2012a**]. For this reason, especially architects should be ready to propose advanced energy efficiency renovations strategies to overcome the actual tendency, and influence the order of the reasons for which a building owner decides to renovate by showing what feasible strategies should be considered to achieve more ambitious objectives.

During the renovation process, the main problems detected between the different stakeholders (architects, engineers, owners and contractors) are related to a lack of: common objectives, project integration and communication, and time dedicated on the design task and for comparing new solutions to choose the best package of energy-efficiency measures [**Palm et al. 2018**]. In general, this limited time for previous analyses entails a decision-making process based on rules of thumbs that do not allow to overcome the inertia of the current practices.

Any architectural project, including energy renovation projects, are characterised by an iterative process. This logic is difficult to understand for certain stakeholders like consultants or owners that would like to obtain a unique result with the optimum solution. Beyond this divergence, an optimum solution is difficult to identify since projects are evaluated according to a diversity of criteria.

As will be seen in the following section, the Swiss energy saving expectations for the 2050 horizon are quite high. For that reason, neither the common practices – which are mainly limited to light renovation interventions – nor the existing regulations will allow reaching the Swiss objectives [**Roger W et al. 2007; OFEN 2018a**]. In response, authorities have launched normative and economic initiatives to promote more efficient renovation projects. To clearly define the framework of this research it is necessary to look at these initiatives.

3.1.3. Promotion of building renovation in Switzerland

Normative framework

As introduced in Chapter 1, the main initiatives at the federal level in Switzerland in terms of energy performance of buildings correspond to the Swiss Energy Strategy 2050 [**OFEN 2018a**] and the related 2'000-Watt Society concept **[SIA 2017a]**, which has two main objectives: 1) limit the consumption of primary energy and 2) reduce greenhouse gas emissions.

The main regulations, standards, and voluntary labels that have implications for practice are the Cantonal Energy Directive (MoPEC) **[EnDK 2014]**, the SIA norms (e.g. SIA 380/1:2016 [**SIA 2016b**]), and the Minergie® label **[Minergie 2018]**.

Cantonal Energy Directive (MoPEC)

The last version of the Cantonal Energy Directive (MoPEC) was published in 2014 **[EnDK 2014]**. This regulation has, as a main objective, to encourage the deep renovation of building envelopes (passive strategies), as well as the replacement of inefficient HVAC systems (e.g. electric resistance (Joule effect) for heating and DHW). In order to prioritise passive over active strategies, freedom in the choice of the new HVAC system is only granted if a certain energy efficiency level of the building enveloped is reached, i.e. category D of the cantonal energy certificate of buildings (CECB) **[Vaillant 2015; EnDK 2018a]**.

In addition, as of 2020, buildings that are significantly renovated will be obliged to mainly use renewable energies for heat production. This directive thus has a significant impact, especially for building managers and contractors, as they determine the conditions to be met in the future for new construction and renovation projects.

This directive is used as a reference to define the different labels and standards to be respected by new and renovated buildings, such as those described below.

SIA 380/1:2016 requirements

The mandatory standard SIA 380/1:2016 **[SIA 2016a]** offers two pathways for justifications: 1) respect efficiency values (e.g. U-value limits of 0.25 and 1 W/m^2·K respectively for opaque elements and openings in renovated buildings), or 2) demonstrate, through energy performance simulation, that a certain limit value for the heating energy demand is respected. This limit value is calculated through an equation (Annexe 10.2) involving factors related to the type of building (residential, office, …) and to its shape factor (ratio between thermal envelope and energy reference floor area), as well as the average outdoor temperature.

SIA 2040:2017 targets

In order to achieve the ambitious objectives of the 2'000-Watt Society within the building sector, the SIA 2040:2017 [**SIA 2017a]** guiding document defines the specific targets to be respected for each building type (e.g. residential, office, school, hotel, etc.) and construction type (i.e. new or renovation). The targets consider the entire life-cycle of the building including the energy consumed and the GHG emissions related to the construction materials (embodied energy), the operational phase (use of the building), and the induced daily mobility of the people using the building. Two main indicators are defined: the non-renewable Cumulative Energy Demand (CEDnr) and the Global Warming

Potential (GWP). For residential buildings, the targets are exposed in Table 3-2 and Table 3-3, respectively in the same units as the 2'000-Watt Society objectives and per building floor area, based on the SIA's hypothesis in terms of surface area per occupant (60 m^2/pers).

Table 3-2. Residential buildings targets according to the 2'000-Watt Society for the intermediate 2050 horizon [**SIA 2017a**].

Housing buildings	CEDnr		GWP	
	W_{NRE}/per·year		$tCO_{2\text{-}eq}$/per·year	
	New	Renovation	New	Renovation
Construction	205	**137**	0.54	**0.30**
Operational	411	**479**	0.18	**0.30**
Induced mobility	205	205	0.24	0.24
Total	822		0.96	0.84
Construction + Operational	**616**		0.72	**0.60**

Table 3-3. Residential buildings targets according to the 2'000-Watt Society for the intermediate 2050 horizon, using 60 m^2 of energy reference area (ERA) per person [**SIA 2017a**].

Housing buildings	CEDnr		GWP	
	kWh_{NRE}/m^2·year		$kgCO_{2\text{-}eq}/m^2$·year	
	New	Renovation	New	Renovation
Construction	30	**20**	9	**5**
Operational	60	**70**	3	**5**
Induced mobility	30	30	4	4
Total	120		16	14
Construction + Operational	**90**		12	**10**

Minergie® label requirements

Minergie® is a Swiss voluntary label that can be used as reference to build high-energy efficiency buildings, and to obtain public subsidies (e.g. *"Programme Bâtiment"* [**EnDK 2018b**]). The last version of the Minergie® label [**Minergie 2018**], published in 2017 and in force since 1st January 2018, sets a consumption limit taking into account the global final energy balance of the building, including heating, DHW, electricity consumption for appliances, lighting and ventilation system. Minergie® proposes three possible labels with different targets as shown in Table 3-4: Minergie®, Minergie®-P or Minergie®-A, the latter corresponding to a positive energy building. The novelties of the 2017 version are that it: takes into account the whole energy balance of the building, prioritises technical systems that do not use fossil fuels, and requires installing a minimum amount of photovoltaic energy in self-consumption mode.

Table 3-4. Summary of requirements of the Minergie® label for renovation projects. ERA: Energy Reference Area. *Corresponds to the final energy balance using specific ponderation factors depending on the type of energy source (e.g. 2 for electricity, 1 for fossil fuels). ** Installed PV power (Wpeak) according to Standard Test Conditions (STC) [**Odersun 2011**] (consisting in applying a light source of 1000 W/m^2 vertically to the cells at an ambient temperature of 25ºC with a light spectrum of 1.5 Air Mass).

	Minergie®	Minergie®-P	Minergie®-A
Consumption index*	90 kWh/ m^2_{ERA}·year	80 kWh/ m^2_{ERA}·year	35 kWh/ m^2_{ERA}·year
Building envelope performance	Comply with MoPEC 2014 and SIA 380/1	Improve by 10% MoPEC 2014 and SIA 380/1	Comply with MoPEC 2014 and SIA 380/1
PV installation	Min 10 Wp/m^2_{ERA} or 30 kWp**		
Consumption without PV*	60 kWh/ m^2_{ERA}·year		

Economic framework – initiatives

Aside from the tax benefits associated to investments in maintenance and renovation interventions (which are deductible from the owner's incomes) [**CH 1990, 2018**], direct economic aids are made available to promote energy efficiency renovation processes through the subsidy program called *"Programme Bâtiment"* [**EnDK 2018b**]. This program focuses on buildings built before 2000 and is rolled out on two levels: National: energy-efficiency measures to improve building envelope, and Cantonal: measures to promote renewable energies, heat recovery and technical installations of the building. For example, in the canton of Neuchâtel the application of the *"Programme Bâtiment"* offers 3 variants to justify the improvement of the energy efficiency of the buildings:

Variant 1: consists of 5 possible (combinable) improvement strategies offering different subsidies. 1) Thermal insulation of the building envelope, for which 60 CHF/m^2 of insulated area are received, with a requirement in terms of thermal transmittance (U-value less than 0.20 W/m^2·K). 2) Replacing an oil-boiler by a biomass-boiler, for which 100-180 CHF/$kW_{thermal}$ are granted. 3) Replacing an electric-boiler (Joule effect) by a heat-pump, obtaining 60-180 CHF/$kW_{thermal}$. 4) Connecting to an urban district heating system, 10-40 CHF/$kW_{thermal}$ granted. 5) Installation of solar thermal panels for DHW and/or heating, to obtain up to 500 CHF/$kW_{thermal}$.

Variant 2: consists in improving the global energy performance of the building for which 35-155 CHF/m^2 of energy reference area can be obtained depending on the number of classes improved based on the Cantonal Energy Certificate of Buildings (CECB).

Variant 3: consists in obtaining one of the three Minergie® renovation labels (Minergie®, Minergie-P® or Minergie-A®) to receive between 100-155 CHF/m^2.

In addition, communal subsidies for Neuchâtel are also available as a +15% bonus on top of the *"Programme Bâtiment"* for thermal insulation measures **[Ville de Neuchâtel 2018]**.

CO_2 taxes evolution

Switzerland is making a considerable effort in the promotion of renewable energies for the progressive exit from nuclear energy **[AFCF 2018]**. However, as can be seen from Figure 3-1, the majority of buildings still use fossil fuels for heating, with 47.3% using oil, 16% natural gas, and the rest (36.7%) relying on electricity (9.6%), wood (12%), heat-pump (11.9%), solar thermal (0.3%), district heating (2%), or other (0.9%) **[OFS 2015a]**.

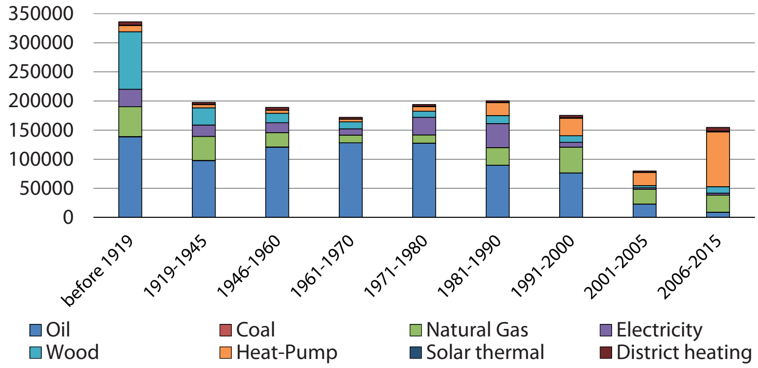


Figure 3-1. Number of buildings in Switzerland according to the type of energy source used for heating and the construction period **[OFS 2015a]**.

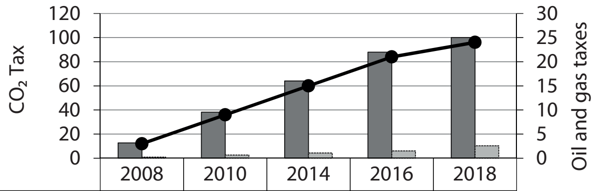
CO_2 emissions due to building-related use of fuels decreased from 23.4 (in 1990) to 17.5 (in 2017) millions of tons, with buildings still responsible for 49.1% of the total CO_2 emissions in Switzerland in 2016 **[OFEV 2017]**.

In 2008, the confederation implemented the CO_2 tax, i.e. taxes on fossil fuels, in order to encourage the use of alternative energy sources. This tax has continuously increased since 2008, as seen in Figure 3-2 **[IMALP 2018]**. Its impact on the final heating oil prices represented a +7%/year for the years 2016-2018 **[Deville Mazout sàrl 2018]**).

In addition to the CO_2 tax, the final oil prices present large variations during the year, fluctuating in 2018 between 85 and 100 CHF/100 litres (representing between 0.085 and 0.100 CHF/kWh$_{thermal}$ including taxes), according to MIGROL [**MIGROL 2018**], a local supplier in Switzerland.

Although natural gas, which costs about 0.080 CHF/kWh$_{thermal}$ including taxes [**Viteos 2018**], is still cheaper than oil, its cost increased by 110% per year for the period of 2008-2018. This price augmentation has mainly been motivated by the rise in the demand for natural gas to the detriment of oil, as well as by the implemented CO_2 taxes.

It is important to specify that the use of a CO_2 tax to motivate renovation is one of the easiest mechanisms, but it is difficult to evaluate the real impact of this measure. Indeed, according to Phillipe Thalmann, professor of environmental economics at the EPFL, *"[…] as an economist, I prefer taxes to interdictions, but in the environmental domain, it's different. […] A tax means that if you pay enough money, you can still [continue degrading the environment]. In a domain as important as that of the climate, this is not fair."* Interview on the RTS radio (08.08.2018) **[RTS 2018b]** (translated from French, own translation).



	2008	2010	2014	2016	2018
Oil Tax (CHF/100 liters)	3.18	9.54	16	22	25
Gas Tax (cent.CHF/kWh)	0.22	0.65	1.09	1.52	2.59
CO_2 Tax (CHF/tnCO_2)	12	36	60	84	96

Oil Tax (CHF/100 liters) Gas Tax (cent.CHF/kWh) CO_2 Tax (CHF/tnCO_2)

Figure 3-2. Evolution of the CO_2 tax in Switzerland, per fossil fuel type (oil and natural gas) and expressed per ton of CO_2 [**IMALP 2018**].

3.1.4. Towards holistic PV-integrating renovation strategies

The decarbonisation of the building stock – objective of the latest Energy Performance of Buildings Directive (EPBD) **[EU 2018]** – cannot be achieved only with classic renovations (i.e. increasing the insulation of the building envelope and replacing the existing boiler). It is indeed necessary to integrate renewable energies such as photovoltaic solar energy **[E2B et al. 2012]**, if carbon neutrality is to be achieved in the renovation process [**Schwede et al. 2017**].

In this sense, the integration of PV elements when a building is to be renovated, using as potentially active surfaces both the façades and the roof, is no longer an option but a necessity. This is to be done through a holistic vision involving complementary strategies and in particular the Building-Integrated Photovoltaic (BIPV) concept. As mentioned in [**Zanetti et al. 2017**], the increasingly stringent European regulations [**EU 2010, 2012a, 2018**] shall become important drivers for the progressive inclusion of BIPV in the building sector. The BIPV concept is introduced in the next section, dedicated to the state of the art on photovoltaics in architecture.

3.2. Photovoltaics in architecture

This section presents the framework related to the integration of photovoltaics in buildings and their application within renovation processes. We first introduce the concept of Building-Integrated Photovoltaic (BIPV), before presenting a brief review of the state of the art regarding the different technologies and available products, and best practices in renovation projects. The main barriers and opportunities are then discussed, as well as the initiatives to promote PV in the Swiss context.

3.2.1. Building-Integrated Photovoltaics

The installation of photovoltaic energy in buildings typically consists in adding a layer on the envelope of the finished building. This layer does not fulfil any function other than producing electricity; it has no building envelope functionality and simply uses the building as a structural support [**Peng et al. 2011; Jelle et al. 2012a, 2012b**]. This concept is called Building-Added (or Attached) Photovoltaics (BAPV) and involves the use of low-cost standard PV panels to maximise annual production, often neglecting the aesthetics of the building.

Because of this, the image that we all have in mind – of dark blue PV panels with a shiny aluminium frame on top of a terracotta-tiled roof – is an image that provokes rejection at the time of thinking about the implementation of a photovoltaic installation on existing buildings. Currently, as we will see in the following sections, the offer of products that are much more adapted to buildings is very broad, and most of these products already have the capacity to replace construction materials [**Munari Probst et al. 2012; Swissenergy et al. 2018**].

Such products respond to the Building-Integrated Photovoltaics (BIPV) concept, which is based on the idea of replacing an inert construction material with another that meets the same constructive requirements while also having the function of producing electricity. BIPV products are used as part of the building envelope (covering element of the roof, façade cladding, glass surfaces, etc.), as sun protection devices (shading), architectural elements or accessories (such as canopies, balcony parapets, etc.), and any other component necessary for the proper functioning of the building.

The BIPV concept, as typical in the building and architecture domain, involves two complementary aspects: the multi-functionality of the solar component (functional/constructive integration), and its formal integration in terms of architectural quality [**Munari Probst et al. 2012**]. This definition therefore excludes *"independent"* or *"overlapped"* installations such as PV modules simply placed or mounted on pre-existing roofs or merely attached to parts of the building and that do not assume any other function than the solar electricity generation (i.e. BAPV) [**Peng et al. 2011; Jelle et al. 2012a, 2012b**].

While the functional and architectural integration aspects fulfilled by BIPV elements vary across products, according to the breNational Solar Centre in the United Kingdom [**Boyd et al. 2018**], typical products provide at least three out of the following features: aesthetic design, structural component, electricity generation/CO_2 reduction, electrical efficiency, soundproofing, thermal control, weather protection, shading/ modulation of daylight, visual obscurity and whole-life costs compared to conventional materials.

In light of its multi-functionality, the integration of BIPV should be understood and designed/assessed in a global way, starting from the first phases of definition of a project. Specifically, in the context of renovation, the needs of the building must be considered to identify how the generated electricity will be used in order to coherently dimension the installation. This is a task that architects must be able to undertake.

Common practice in terms of BAPV is to maximise the yearly energy production, by positioning large quantities of PV panels on optimally-oriented surfaces [**Sánchez et al. 2015**]. In the case of BIPV used in existing buildings, it is not appropriate to have the same objective, partly because the orientation of the different surfaces of the building are fixed. However, as argued in [**Sánchez et al. 2015**], BIPV elements can be cost-effective even when installed in non-optimal orientations, if a self-consumption (SC) approach is adopted. Self-consumption refers to the share of the total PV production that is directly consumed by the producer, i.e. the building on which the PV system is installed or the owner of the installation, who then become 'prosumers' (producers and consumers) [**Luthander et al. 2015; Summermatter et al. 2015**]. Computing the self-consumption ratio therefore requires comparing the production to the need in real-time, typically through an hourly load matching approach. PV elements situated on façades can help to better match the energy demand, particularly in residential buildings where the energy consumption is mainly during early morning and late afternoon when the sun is lower. A concept complementary to SC is that of self-sufficiency (SS), indicating the level of autonomy of the building and defined as the ratio between the PV electricity consumed by the building (as in the SC) and its total electricity need [**Luthander et al. 2015**]. The relevance and meaning of these concepts in relation to BIPV in renovation is further addressed in the following sections.

3.2.2. Technology, products and best practices

This section offers an overview of the current status of PV technology, of the available products and personalisation techniques, and of the possibilities of energy storage and related installation elements. Some examples of renovation projects that use photovoltaic products in the design of façades are also presented.

Existing and emerging technologies

The use and development of photovoltaic technologies and products available have over 20 years of history. The existing and emerging PV technologies can be studied through different types of classifications found in the literature. One such classification is based on the maximum efficiency that can be achieved with each technology. Presented in the *"Best Research-Cell Efficiencies"* chart (Figure 3-3) elaborated by the National Renewable Energy Laboratory (NREL) [**NREL 2018**], PV cells are grouped into 26 different subcategories within five different families of technologies: 1) multi-junction cells, 2) single-junction gallium arsenide cells, 3) crystalline silicon (c-Si) cells, 4) thin-film technologies and 5) emerging photovoltaics (i.e. dye-sensitised cells, perovskite cells, organic cells). It can be observed that the multi- and single-junction cells have the highest efficiency, whereas emerging technologies are still at the lower end of the efficiency range, but are improving very fast compared to more mature technologies. The most common crystalline silicon cells are in the middle of the pack with an efficiency around 25%.

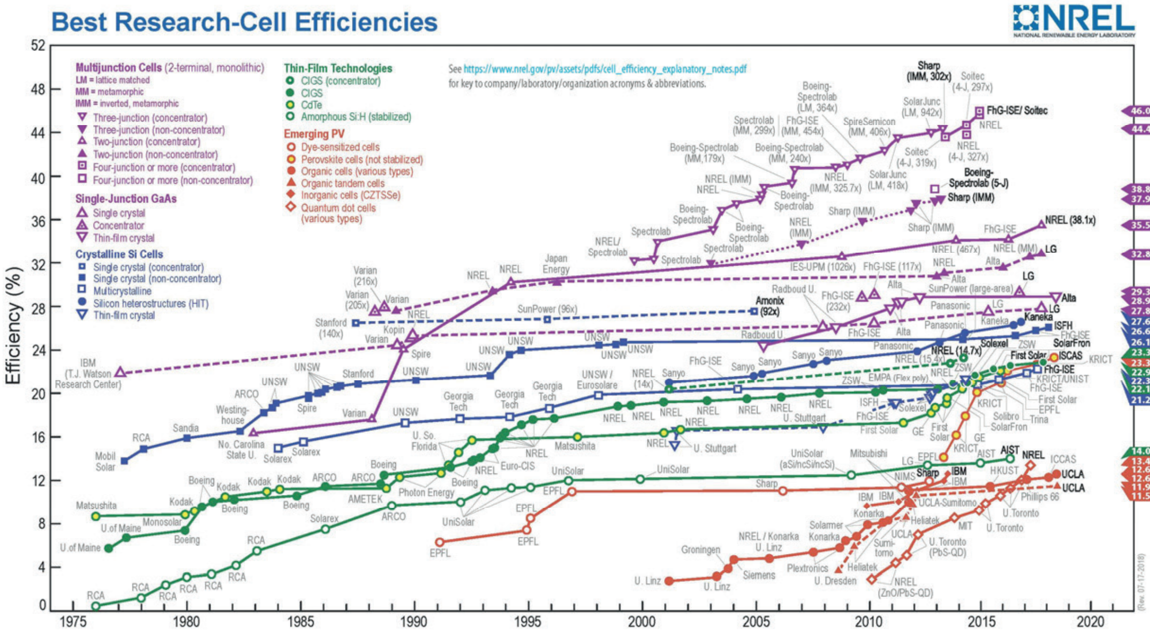


Figure 3-3. Best research-cell efficiencies by technology [**NREL 2018**]. The chart shows the values of the highest confirmed conversion efficiencies for research PV cells (from 1976 to the present), obtained in Standard Test Conditions (STC) [**Odersun 2011**] (consisting in applying a light source of 1000 W/m² vertically to the cells at an ambient temperature of 25ºC with a light spectrum of 1.5 Air Mass).

A classification can also be made based on the maturity of each technology, where maturity here relates to the actual use in practice – influenced by the viability of the technology for ensuring reasonable stability and lifetime of PV modules – and not to the invention year shown in Figure 3-3. This classification leads to three generations [**Shukla et al. 2016**] that include: 1) silicon mono-crystalline (mono-Si) and poly-crystalline (poly-Si) PV cells, the most mature and used technologies that continue to evolve, as the amount of material necessary for manufacturing them using more efficient techniques are decreasing, and therefore so is their economic cost **[Fraunhofer ISE 2018]**, 2) the amorphous silicon (a-Si), Cadmium telluride/sulphide (CdTe) and Copper indium gallium selenide (CIGS) PV cells, and 3) the most recent technologies such as Copper zinc tin sulphide, Dye-sensitised, Organic, Perovskite, Polymer and Quantum dot PV cells.An overview of the main mature and emerging technologies is presented in Figure 3-4, with information notably on their efficiency and lifetime.

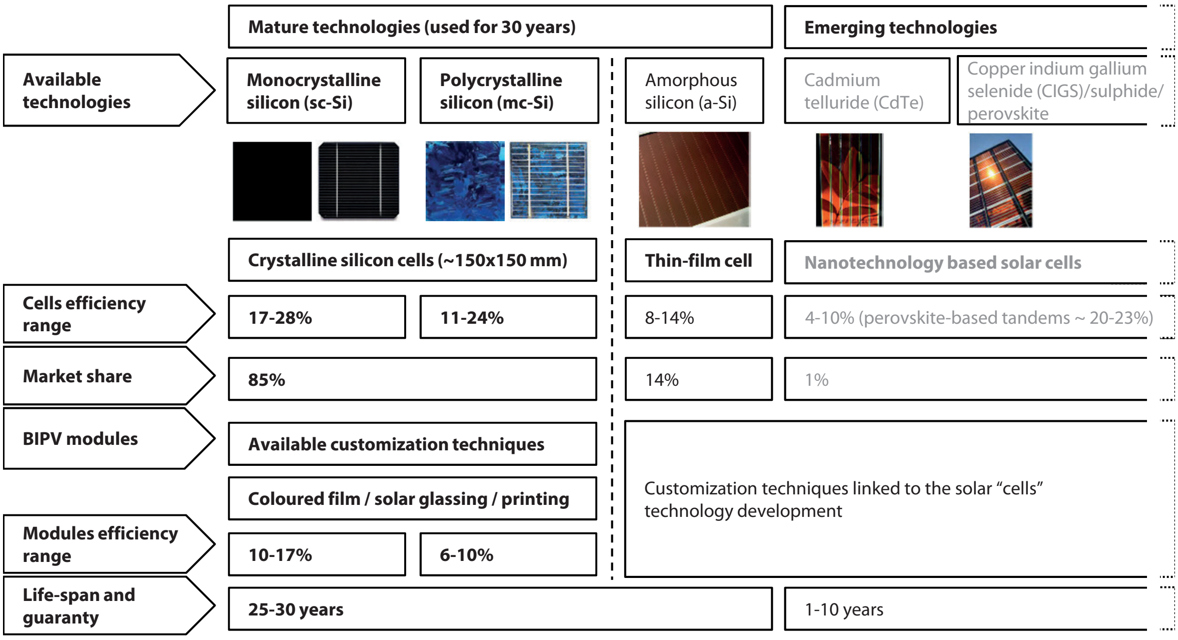


Figure 3-4. Summary of the most used PV technologies in buildings (adapted from **[Munari Probst et al. 2012]** and updated using data from **[NREL 2018]**).

Besides technology-related features, one of the parameters that is most used to show the evolution of photovoltaic technology is the cost of the electricity produced by a PV installation, also named Levelized cost of electricity (LCOE). The LCOE considers the cost of the PV elements, operational and maintenance costs over the system lifetime, replacement of equipment, the efficiency of the used technology, and the built context surrounding the installation. According to Solar Power Europe and the European Photovoltaic Industry Association (EPIA), the cost of solar energy decreases as the industry reduces its cost and installation becomes more common and efficient. As shown in Figure 3-5, both in southern and in northern Europe, projections made in 2013 show that the cost of PV electricity from utility-scale systems was expected to soon become cheaper than the retail electricity from the grid (household electricity price) **[EPIA 2013]**. Similarly, **[Kost et al. 2013]** predicted that by 2030, the PV LCOE could drop to 0.043-0.064 €/kWh in areas with high annual irradiation levels (i.e. in the order of 2000 kWh/m^2·yr (e.g. southern Spain) and more). Such projections of a decrease in the LCOE for large-scale PV plants and their competitiveness with other renewable energies, with fossil fuel power plants, and the grid electricity cost are in fact widespread and global **[EPIA 2013; Kost et al. 2013; IRENA 2016; SolarPower Europe 2017]**. However, much less information can be found regarding small-scale BIPV installations, particularly for the residential building sector. As addressed later in Section 3.2.3, the economic assessment of BIPV systems is more complex than for utility-scale or BAPV installations, due to the additional functionalities of BIPV mentioned earlier.

Cost reductions are made possible by the technological advances in solar PV modules, manufacturing improvement, economies of scale, and the reduction in the cost in the Balance of System (BoS) **[IRENA 2016]**. The BoS includes all system components aside the panels themselves, i.e. the wiring, connections, mounting system, solar inverters and storage systems (batteries and chargers' controllers). Many publications show that the biggest cost reduction opportunities are at either end of the value chain of the PV modules using crystalline silicon technology **[IRENA 2016; Yang et al. 2016; SolarPower Europe 2017; Bonomo et al. 2018]**. It is also highlighted that 30% of the total cost reduction potential of will come from the cell to module manufacturing phase.

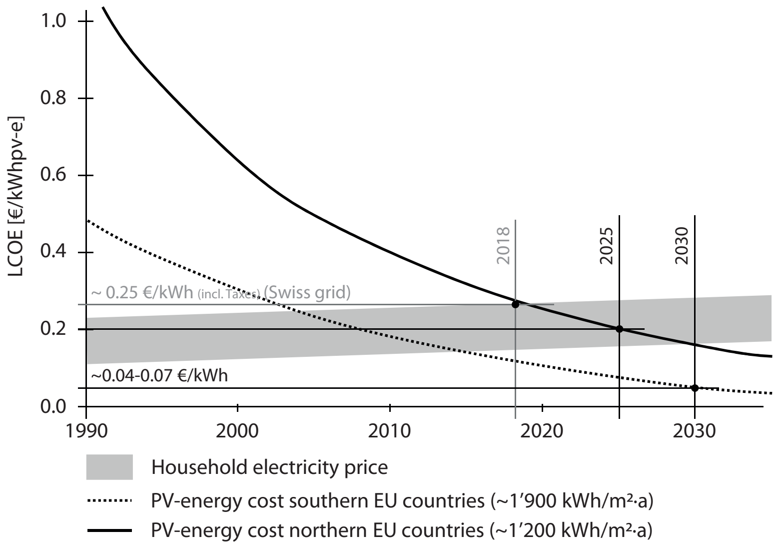


Figure 3-5. Projections made in 2013 for the Levelized cost of electricity (LCOE; €/kWh) of grid-connected large PV installations in northern and southern European countries (curves), compared to the household electricity price range **[EPIA 2013]**; the PV LCOE is expected to reach 0.04-0.07 €/kWh by 2030 [**Kost et al. 2013**]. For comparison, the price of grid electricity in 2018 in Switzerland is around 0.25 €/kWh (incl. taxes) [**Solar Power Europe 2018**].

For solar wafers and cells manufacturing, most of the producers have implemented lower-cost diamond-wafer technology, achieving low-cost and high-efficiency cells using almost exclusively the monocrystalline technology [**SolarPower Europe 2017**]. One of the most relevant improvements on the photovoltaic modules comes from the so-called *"half-cells"* technology, that reduces the series resistance losses by four and the risk of hot-spots in partial shading situations. Likewise, the use of bifacial cells can easily exceed 20% efficiency but this technology is not adapted to be applied on opaque surfaces of buildings as a façade-ending material. Inverters have also evolved; in the first solar power stations, large centralised inverters were used, and this practice is definitely over. Today, the use of small string inverters has become widespread, allowing easy maintenance and helping to deal with possible partial shading problems that can occur when panels are installed in multiple orientations (e.g. façades), a situation particularly present in dense urban environments. Indeed, in such cases, power optimisers combined with a division of the system according to the different façade orientations through distinct DC/AC inverters or micro-inverters can dramatically reduce the impact of partial shading [**Ikkurti et al. 2015; Couty et al. 2017**].

Recyclability of mature technologies

The Swiss Federal Council, in a statement from 2012, highlighted that the first PV panels achieving their end of life (after 25-30 years) would appear around 2015 [**Vogler 2012**]. Indeed, mature technologies such as silicon-based PV modules – which represent over 95% of the total market share as shown in Figure 3-4 – have been on the market for over 30 years.

Currently, PV module waste are treated as general waste in the regulations, except at the EU-level, where they are classified as electronic waste (e-waste) through the Waste Electrical and Electronic Equipment (WEEE) Directive [**Sykorova et al. 2018a**]. This Directive [**EU 2012b**], in force since 2012, plans for a progressive implementation of recycling requirements, achieving full implementation in 2018, as illustrated in Table 3-5.

Original (2002) and revised versions of the WEEE Directive	Annual collection targets	Annual recycling/Recovery targets
2002/96/EC	4 kg/inhabitant	75% recovery, 65% recycling
2012/19/EU, up to 2016	4 kg/inhabitant	Start with 75% recovery, 65% recycling, 5% increase after 3 years
2012/19/EU, from 2016 to 2018	45% (by mass) of all equipment put on the market	80% recovered and 70% prepared for reuse and recycled
2012/19/EU, from 2018 and beyond	65% (by mass) of all equipment put on the market or 85% of waste generated	85% recovered and 80% prepared for reuse and recycled

Table 3-5. Annual collection and recovery targets (% mass) under the WEEE Directive. Table adapted from [**Weckend et al. 2016**].

Based on current recycling techniques, a high percentage of the material (in terms of mass) can already be recycled, as shown in Table 3-6 for silicon-based technologies. Overall, 96% of the materials can be reused for producing new solar panels [**Sykorova et al. 2018a**]. The 4% that is left typically includes residues from the glass recovery phase as well as ethylene vinyl acetate (EVA) foils, which can be used as a heat source [**Kenning 2017**].

	Crystalline (c-Si) PV modules		**Amorphous (a-Si) PV modules**	
	Composition	Recyclability	Composition	Recyclability
Glass	76%	95%	89%	90%
Plastic / foils	10%	reused as heat source	4%	0%
Aluminium	8%	100%	6%	100%
Metals and semiconductors	6%	100% (metals) 85% (silicon)	1%	95%
Modules reused		*80%*		-

Table 3-6. Composition and recyclability (in mass) of silicon-based PV modules (based on data from [**Sykorova et al. 2018a**]).

Although recyclability percentages are similar between c-Si and a-Si PV modules, the recycling process are distinct between these two technologies [**Sykorova et al. 2018a**]. Crystalline PV modules can be disassembled and consequently, 80% of the modules can be reused. However, this is not the case for amorphous PV modules, as the process begins by shredding the panels into small pieces (4-5 mm) in order to remove lamination. Moreover, the process involves chemical processes.

Given that PV waste is expected to go from 43'500 tons in 2017 to 60 million tons by 2050 [**Sykorova et al. 2018a, 2018b**], specialised recycling plants are in place in Germany and Italy [**PV Cycle 2016**] and emerging in France [**Kenning 2017**].

In the next section, we move on from the fundamental PV technologies presented in this section to reviewing the main products available on the market that correspond to the BIPV concept.

Products and Customisation techniques

From the point of view of architectural design, and within the context of defining a renovation project using PV systems, it is essential to know the palette of available products, including information on their dimensions, adaptability in terms of size, texture and appearance, technical and environmental characteristics, and how they can be used. As such, we here give an overview of the state of the art regarding available BIPV products, low-cost customisation techniques, batteries and other storage systems, and BIPV-compatible HVAC systems.

Available BIPV products

Existing photovoltaic products and their technical characteristics can be found in various catalogues or databases such as **[CEC et al. 2018; Photon 2018; PV Database 2018; Swissenergy et al. 2018]**. For instance, **[CEC et al. 2018]** lists flat PV modules following a classification based on:

- Type of integration: BAPV versus BIPV
- Nominal power
- Family: Monocrystalline, Polycrystalline, Thin Film, CIGS and HIT-Si.
- Technology: mono-Si, poly-Si and a-Si
- Electrical features
- Efficiency
- Dimensions

From the 21'241 listed products, only 162 (about 1%) are considered as BIPV elements, and 54% use the mature poly-Si technology (Figure 3-6).

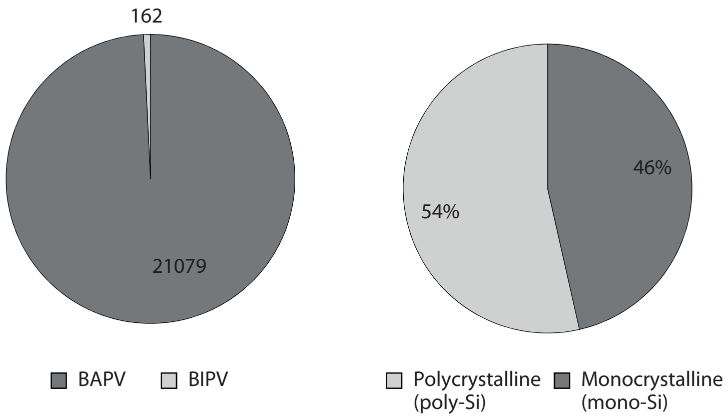


Figure 3-6. PV product classification according to the integration (BAPV, BIPV) and the technology used **[CEC et al. 2018]**.

As can be seen from the top graph in Figure 3-7, BAPV module sizes range from below 1 m^2 to over 5 m^2, with an average size of 1.7 m^2 and an average shape ratio (length of side 1 / length of side 2) of 0.6. Generally smaller, BIPV modules have an average size of 1 m^2 and a mean shape ratio of 0.4. The majority of BIPV modules in fact have a size similar to that of standard (non-active) façade panels such as the Eternit panels, which measure between 0.5-1 m of length and 0.3-3 m of width **[Eternit 2018a]**.

As observed in the bottom graph of Figure 3-7, BIPV panels are generally either small (cluster with short and long side lengths respectively below 0.5 and 2 m) or large (products at the upper and right-most areas of the graph).

In the Swiss context, 80% of the BIPV market is for roofs and only 20% for façades **[Shukla et al. 2017]**. An example of BIPV for roof is Tesla's Solar Roof **[Tesla 2018]** products, which have benefitted from an important media coverage. These represent highly-aesthetical products consisting of small components imitating traditional tiles. This approach is common for roof BIPV elements and has led to the design of much more integrated solutions than the previous (BAPV) products. However, small elements have the disadvantage of increasing the number of connections necessary and the implementation cost, negatively affecting the reliability of the installation. For these reasons, BIPV products for roofs are increasingly more focused on full-roof solutions using larger elements for a higher efficiency of the whole installation. Indeed, as reflected in **[SUPSI 2018]**, the emerging approach for traditional sloped roofs is to cover the entire surface with both active and non-active elements of the same aspect (the latter usually named *"dummies"* or *"inert"* elements). In this way, it is easier to adapt to the existing geometry of the roof and to obtain an homogenous appearance **[3S Solar Plus AG 2018]**. An example application of this technique can be seen in Figure 3-8.

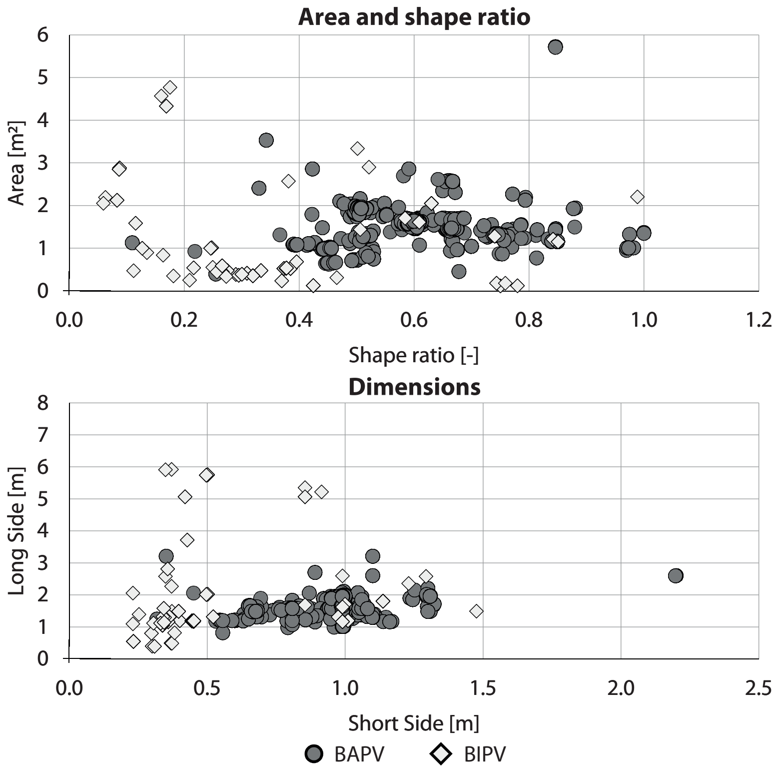


Figure 3-7. Area and shape ratio (top) and standard dimensions (bottom) of BAPV and BIPV modules according to **[CEC et al. 2018]**.

Figure 3-8. Example of active and non-active (*"dummies"*) elements of same appearance, using the Megaslate® BIPV panels from 3S Solar Plus **[3S Solar Plus AG 2018]**. Roof renovation of the Hotel des Associations in Neuchâtel (Switzerland) **[CSEM 2017]**.

The Eternit company **[Eternit 2018b]** develops some solar systems for roof and façade combining their classic (non-active) panels and PV elements with compatible size. For instance, their full-roof Integral2 system includes PV modules of 110-190 Wp with dummies (non-active classic Eternit panels). For ventilated façades, their Elcora2 system allows designers to obtain homogeneous visual results using a mature technology, coming from the company's extensive experience with ventilated façades, to fix the active elements.

In terms of BIPV used for façades, a common product is the semi-transparent photovoltaic glazing to be applied on windows, thus replacing normal glazing. Such products are particularly recommended for office buildings where the window-to-wall ratio is larger than in residential buildings, as they offer a way to activate the façades, control solar gains and reduce cooling loads **[Martellotta et al. 2017]**. However, they have a limited efficiency (below 10%) **[Tina et al. 2013; Yeop Myong et al. 2015]**. Such products are not appropriate for residential buildings where windows are generally smaller, operable, and where there are usually solar protections (e.g. blinds) that could be shading the windows depending on the occupant behaviour. The same is true for BIPV shading devices **[Sun**

et al. 2010; Jayathissa et al. 2016] that are mainly conceived for commercial and office buildings and rarely applied in residential buildings.

As residential buildings require BIPV products above all to cover (or build) the opaque parts of the building envelope, flexibility in the product manufacturing is more important than having a multitude (wide range) of standardised sizes. Indeed, flexibility is necessary to accommodate the diversity of façades, particularly important in renovation projects [**Zanetti et al. 2017**]. While we also observe large PV elements within the 20% market share for façade BIPV, the industry is slowly starting to offer more flexibility by bringing together the know-how from both the solar and the glass manufacturing industry [**Siemens AG 2012; Sejak et al. 2015**]. As proposed by [**metsolar 2018a; Onyxsolar 2018a**], crystalline silicon PV elements can be fully customised for each project in terms of colour, texture, shape, size (up to 4'000 x 2'000 mm) and free layout cells disposition. With the nominal power of each element defined by the number of cells, Onyxsolar recommends designing a façade in such a way as to reduce as much as possible the number of different sizes (thus of different nominal powers), in order to optimise the installation regarding investment, connections, and operational-maintenance cost. They offer two basic product types: standard panels (prefabricated PV panels ready to be supplied) and custom PV elements with the only design constraint being to respect the maximum measures imposed by the manufacturing process.

Low-cost customisation techniques

Apart from diversity in available sizes, emergent customisation techniques such as low-cost colour customisation are expected to increase the penetration of BIPV in the renovation sector of residential buildings [**Hille et al. 2018**]. A classification of these techniques is shown in Figure 3-9 and information on their efficiency, cost and other characteristics is given in Table 3-7. Depending on the colour and the technique used, the efficiency loss varies between 8-40% with respect to the original module's efficiency. This loss explains why most manufacturers of such products currently use as basis the most efficient PV panel, i.e. mono-Si that has over 20% of efficiency in STC.

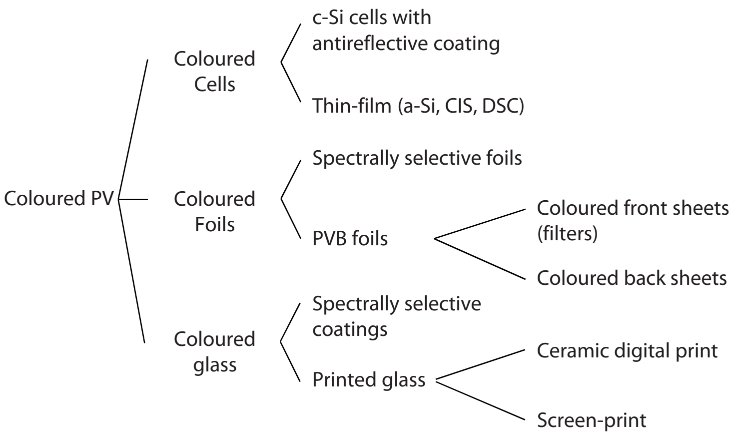


Figure 3-9. Classification of the current low-cost customisation techniques [**DETAIL green 2017**]. c-/a-Si: crystalline-/amorphous-silicone; CIS: copper-indium-selenium; DSC: dye-sensitised cells; PVB: polyvinyl butyral.

To obtain coloured PV panels, one solution on the market, named Kromatix, is based on colour coating on treated glass [**Emirates Insolare et al. 2018**]. This is the kind of BIPV modules installed in the Copenhagen International School and in the Kohlesilo in Basel, one of the most internationally-known BIPV façades.

	Coloured c-Si cells	Dye-sensitised solar cells	Foil	Colour coating on treated glass	Coloured screen-print	Digital print on glass
Efficiency loss through colour	10-14%	-	10-40%	12-19%	15-60%	10-40%
Resulting module efficiency (reference: 17 %)	10-15%	2-4%	10-15%	13-15%	7-14%	10-15%
Additional cost for coloured layer	-	-	75-150 €/m2	70 €/m2	>50 €/m2	75-150 €/m2
Number of colours available (2017)	10	10	8	8	Unlimited	Unlimited
Manufacturer	Sunshine PV / LOS Solar	Solaronix	Solaxess / Issol	SwissInso / Emirates Insolaire	Ertex, ViaSolis, Hero-Solar, Issol	ÜserHuus, ertex

Table 3-7. Technical features of commercialised coloured BIPV elements using low-cost customisation techniques. Table adapted from **[DETAIL green 2017]** with data from **[Solaxess 2018]**.

Figure 3-10. Example of BIPV modules with a coloured film **[CCEM 2012b]**. Photo: P. Heinstein.

The Centre Suisse d'Electronique et Microtechnique (CSEM) **[CSEM 2018]**, who works on the visual appearance (colours and textures) of PV elements to help the integration in buildings, has developed coloured panels using one of the most promising low-cost customisation techniques. This technique is based on the introduction of a radiation-selective layer (selective filter; foil technique) between the encapsulation layers, using standard solar glass and crystalline-silicon based PV panels. Example BIPV modules produced using this technique are shown in Figure 3-10. Developed in the framework of the Archinsolar research project **[CCEM 2012b]**, such products are now commercialised by SOLAXESS **[Solaxess 2018]** and ISSOL **[ISSOL 2018]**, and real applications can now be found in the Swiss context.

For this foil technique, depending on the colour, the final efficiency of the module is affected; the clearer the colour, the greater the loss in efficiency. For white or light grey, the efficiency loss can reach up to 40% because the filter blocks the passage of the irradiation in the visible spectrum (only the infrared (IR) part of the spectrum passes through). Figure 3-11 shows the reflectance/transmittance for different film colours along with the efficiency loss compared to a standard panel without film (transparent) **[DETAIL green 2017]**.

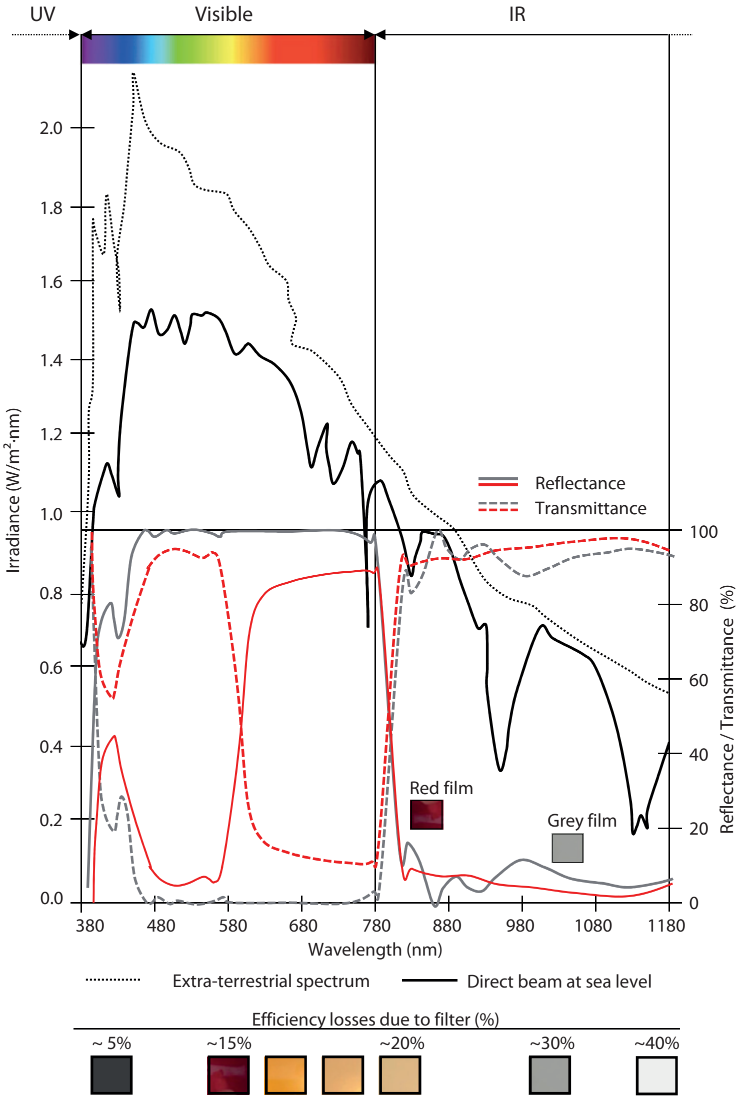


Figure 3-11. Reflectance/transmittance (graph) and efficiency loss (bottom) of different coloured BIPV modules **[DETAIL green 2017]**. For example, a red-coloured film reflects the red part of the visible spectrum and transmits most of the remaining part including the infrared (IR) portion of the spectrum. Its efficiency loss is of around 15% with respect to a standard PV panel (no film; transparent).

An analysis of the cost distribution among the different components of a BIPV installation for an example renovated residential building is shown in Figure 3-12 **[Zanetti et al. 2017]**. The additional cost related to each customisation technique shown in Table 3-7 falls within the 26% attributed to the solar modules. Given this price distribution, which considers a complete BIPV installation, it is evident that the decrease in the price of the BIPV modules themselves (including or not customisation costs) has a significant but limited impact on the total price of the installation. This is an important point to consider when evaluating the implementation of a BIPV installation on an existing building. In most cases, a BIPV installation only – without any interventions for improving the building envelope (i.e. insulation) – will be economically difficult to justify, mainly because of the cost related to the installation phase, for example, the additional cost of renting the scaffolding particularly for installations on façades. In this sense, it is more efficient to consider the BIPV installation within the entire renovation process, using the scaffolding for both purposes (i.e. BIPV installation and insulation of façade), avoiding the repercussion of the price of the scaffolding only to the photovoltaic installation.

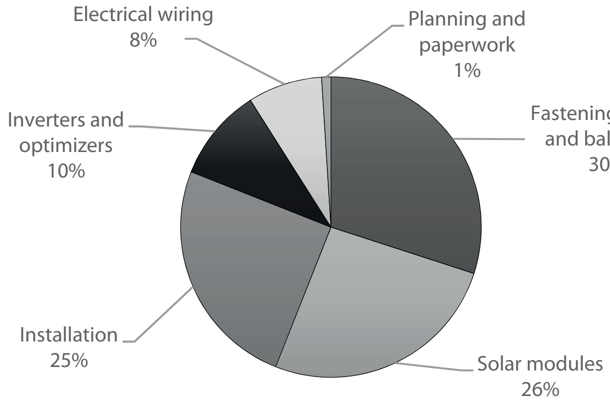


Figure 3-12. Distribution of cost for façade BIPV based on a multi-story refurbished residential building located in Ticino, Switzerland [**Zanetti et al. 2017**]. In this example, the total cost (excluding scaffolding cost and taxes) is of 410 CHF/m^2 of installed PV surface.

Batteries, storage systems, electric vehicles and BIPV-compatible HVAC systems

Apart from designing BIPV installations well-adapted to the building needs, e.g. through an adequate number of active elements and proper positioning, the efficiency of the whole system can be further enhanced using auxiliary equipment that enable increasing the self-consumption ratio.

The main strategies put forward to increase the SC ratio of a PV installation, listed in Table 3-8, are: 1) producing heat with photovoltaic current (i.e. using BIPV-compatible HVAC systems for heating and DHW), 2) operating household appliances with solar current (i.e. using demand-side energy managers), 3) charging electric vehicles (EV), or 4) storage in accumulators (i.e. stationary batteries or EV) [**Suisse Energie et al. 2015; Fraunhofer ISE 2018**].

Through the first strategy – using a BIPV-compatible HVAC system for heating and DHW – the active BIPV envelope can further fulfil the real needs of the building. This strategy is particularly relevant in the context of renovation, where the global performance of the installation (i.e. the SC ratio) can be increased by substituting the existing HVAC system by a heat-pump based system [**Niederhäuser et al. 2014**].

Final use objective and transformation system	Efficiency values
Heat production	
Heat-pump (η=300%) + Heat storage water tank (η_{th}=90%)	**η=270%**
Self-consumption of electricity	
Stationary batteries (η=90%)	**η=90%**
Mobility using private vehicles	
Battery and electric motor (η=85%)	**η=85%**
Electrolysis compression H_2 (η=75%) + Fuel cells, electric motor (η=60%)	**η=45%**
Electrolysis methanation, compression CH_4 (η=70%) + Combustion engine (η=30%)	**η=21%**

Table 3-8. Indicative efficiency values of most common conversion means and PV storage [**Fraunhofer ISE 2018**].

However, the question about which is the most appropriate system to produce DHW from renewable energy in a residential building should be asked for every case. Although in some EU countries solar thermal (collectors) systems are often the first go-to solution [**EnDK 2014; MF 2017**], the final choice should be made depending on the context and the location of the building. For instance, according to a study by [**Wei et al. 2014**] in the context of China, if the surface available on the roof exceeds 4 m^2 per apartment, a BIPV system combined with a highly-efficient heat-pump is usually more profitable than thermal collectors.

New heat-pump systems are thus being proposed on the market, such as the heat-pump with Smart Grid (SG) Ready technology [**Suisse Energie et al. 2015**]. This product can adapt its consumption levels to the situation of the PV installation or the smart grid, for example to store heat energy in the water tank during night saver rates or when the maximum PV production occurs. Since the peak PV production typically coincides with the moment when the electricity demand is at its lowest, injection of the overproduction to the grid is in that way avoided. This technology could also be used, as suggested in [**Vuarnoz et al. 2016**], to choose the energy source according to its carbon content. A smarter selection could thus be made among the available energy sources (electrify coming from the grid, from batteries, or directly from the PV installation).

Stationary batteries offer another means of storing excess PV electricity at any given moment. However, as highlighted in [**McManus 2012; Stenzel et al. 2014; Vandepaer et al. 2017**], the environmental impacts of batteries are high when these are used in low-energy buildings, making it even more important to conduct a LCA when incorporating such systems. Out of the different battery technologies, the most extended type are lithium-ion batteries, which have around 10 times less environmental impacts and a longer lifetime (but a higher cost) than the classic lead acid batteries [**McManus 2012; Couty et al. 2017; energysage 2018**]. The lifespan of batteries is characterised by the number of charge / discharge cycles that they can support before losing more than 80% of their nominal storage capacity. Lithium-ion batteries can achieve between 2'000 and 5'000 such cycles, corresponding to over 12 years of lifetime at over 80% of their maximum capacity [**Stenzel et al. 2014; Vandepaer et al. 2017; Swiss-green 2018**].

An alternative to installing stationary batteries in buildings is to use EV with vehicle-to-grid or –to-building operation [**Fraunhofer ISE 2018; Hoarau et al. 2018; Robledo et al. 2018**]. In that way, the use of the electric car's battery as a storage system used by the building allows to increase the autonomy of the building (self-sufficiency) and the efficiency of the BIPV installation (high self-consumption ratio). Although the discharging of the car battery to provide electricity for domestic use is not yet part of the current practice, different manufacturers are working on EV whose battery can be used in a bidirectional way (e.g. Nissan, BYD, Power Box by Mitsubishi).

PV electricity sharing at neighbourhood level (microgrids)

Apart from using electric HVAC systems, batteries or EV, there is also the possibility to share the overproduction of a building's BIPV with neighbourhood consumers (micro-grids) in order to increase the efficiency of the installation [**Couty et al. 2017**]. This is possible in Switzerland, according to the latest update of the Energy Law (LEne), in force since January 1, 2018 [**AFCF 2018**]. This law makes it possible to create microgrids at neighbourhood levels in order to increase as much as possible the self-consumption ratio of photovoltaic installations.

Best practices in renovation projects

We here present successful examples of renovated and new buildings with BIPV in Switzerland, in order to demonstrate the possibilities from an architectural perspective.

The literature review shows that most BIPV studies and applications focus on commercial and office buildings [**Salem et al. 2015; Gindi et al. 2017**], mainly because such buildings present less barriers to BIPV implementation due to (in general) the existence of an owner-occupant. This type of barrier and others are further addressed in Section 3.2.3. There is in fact an insufficient number of aesthetically convincing exemplary buildings of residential renovation projects with BIPV [**SUPSI 2018**]. The few examples found are focused on singular or historical buildings (with a high level of heritage protection), such as churches or monuments [**Heinstein et al. 2013**]. Table 3-9 thus lists examples corresponding not only to renovated residential buildings, but also to new and non-residential buildings that illustrate good practices. Further examples can be found in [**SUPSI 2018**], a large census of new construction projects, as well as in [**OFEN 2018b**] and [**OFEN 2017**] for the most recent flagship projects.

	Description	Architect	Reference
	Residential buildings		
1	**Renovation** of a multi-family building in Chiasso.	TUOR Baumanagement	[Swissenergy *et al.* 2018]
2	**Renovation** of a multi-family building in Romanshorn.	Viridén+Partner	[Swissenergy *et al.* 2018]
3	**Renovation** of a multi-family building in Zurich.	Viridén+Partner	[Knüsel *et al.* 2016] [DETAIL green 2017]
	Non-residential buildings		
4	**Roof renovation** of a 1880's building in Neuchâtel.	Collective Maggmas	[Swiss Solar Agency 2018] [Ballif *et al.* 2018]
5	**Roof renovation** of a farmhouse building in Ecuvillens.	-	[Swissenergy *et al.* 2018] [ISSOL 2017] [Ballif *et al.* 2018]

Table 3-9. A selection of the latest examples of BIPV integration in Switzerland, between 2013 and 2018.

Example 1: Renovation of a multi-family residential building in Chiasso. The strategy includes external insulation with a ventilated façade using frameless glass-glass coloured BIPV panels based on a-Si thin-film technology, mono-Si panels on balconies (semi-transparent) and roof (pergola) **[Swissenergy et al. 2018]**.

Example 2: Solar prix in 2013, this residential building renovation is one of the first buildings in Switzerland to integrate photovoltaic on façade (Figure 3-13) **[Swissenergy et al. 2018]**.

Figure 3-13. Renovation of a residential building using BIPV elements on façade In Romanshorn. Current status (left) and renovation (right). (Copyright Viridén + Partner, Zurich).

Example 3: This is one of the most successful and aesthetically-convincing examples, corresponding to a multi-family residential building renovated in 2016 and located in Zurich. The project consists of a two-floor extension and a completely renovated building envelope (Figure 3-14). Apart from the replacement of the windows, an external insulation is proposed using a ventilated façade system with BIPV elements, totalling to 1'535 m^2 of mono-Si cells modules, custom-sized and visually modified to obtain a grey mat appearance (148 kWp of installed power in STC). In addition, a non-integrated PV installation of 165 m^2 of standard mono-Si PV modules is placed on the roof. This example allows architects to see that it is possible to maintain or improve architectural quality using available products based on mature technology (mono-Si cells) **[Knüsel et al. 2016; DETAIL green 2017]**.

Figure 3-14. Renovation of a residential building using BIPV elements on façade in Zurich. Current status (left) and renovation (right). (Copyright Viridén + Partner, Zurich).

Example 4: Roof renovation of the *"Hôtel des associations des Rochettes"*, an administrative building built in 1880. Shows a fully integrated BIPV installation using black mono-Si cells and completed with specially sized dummy modules (non-active) **[Ballif et al. 2018; Swiss Solar Agency 2018]**.

Example 5: A farmhouse located in a heritage protected area in Ecuvillens, representing a good example of a complete roof renovation using large terracotta tiles based on mono-Si cells in response to the prohibition to use standard PV panels. The efficiency of these visually-customised BIPV panels is about 20% lower than standard PV panels. This installation of 230 m^2 produces around 28 MWh/year (Figure 3-15) [**ISSOL 2017; Ballif et al. 2018; Swissenergy et al. 2018**].

Figure 3-15. Application of coloured BIPV panels commercialised by ISSOL [**ISSOL 2018**] on a rural building in Ecuvillens (Switzerland) [**CSEM 2017**].

3.2.3. Barriers and opportunities

Diverse types of obstacles limit a large-scale advanced PV integration into urban renewal processes. This section presents the main detected barriers and preconceived ideas that no longer hold, as well as the potential benefits and opportunities related to BIPV.

Within the framework of the IEA SHC Task 41 on Solar Energy and Architecture, an international web-based survey was conducted, among others, to identify the main barriers to PV integration perceived by professionals [**Farkas et al. 2012**]. Results, shown in Figure 3-17, point to the economic justifiability as the main barrier both from an international perspective (all respondents; dark bars) and within the Swiss context (grey bars). Also important are the lack of knowledge and interest by clients, lack of knowledge by architects, and limited governmental incentives, datasheets, time and resources.

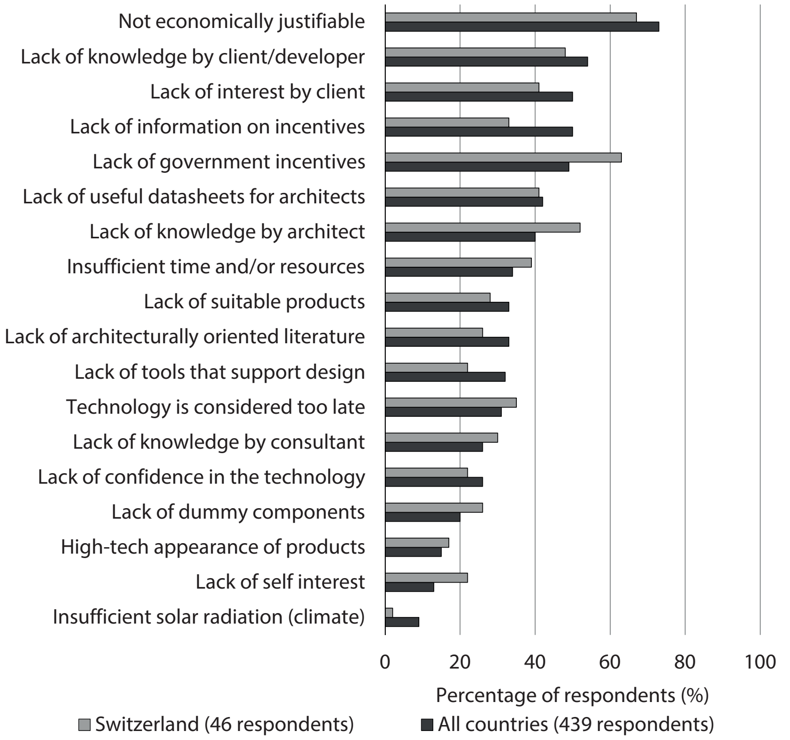


Figure 3-17. Barriers to PV integration selected by all and Switzerland-located respondents (majority of architects/designers) to a web-based international survey (14 countries) conducted within the IEA SHC Task 41 [**Farkas et al. 2012**].

Focusing specifically on façade integration of solar technologies, [**Prieto et al. 2017**] conducted a survey among 79 professionals and analysed the results using the same classification and list of barriers as the IEA SHC Task 41. While 91% of respondents perceive a potential for façade solar integration, economical and product-related barriers were identified as the most pressing to address (Table 3-10).

Main category	Description
Economy	Not economically justifiable and lack of governmental incentives
Product	Lack of products suitable for quality building integration and complementary building components
Knowledge	Lack of sufficient technical knowledge by architect, by client/developer and by consultant
Information	Lack of architecturally oriented literature about these technologies and useful data for architects in product datasheets
Process	Lack of tools that support design and sizing of systems / Technology is considered too late in the design process (insufficient time and resources)
Interest	Lack of interest in solar design by architects and clients/developers

Table 3-10. Barriers listed by the IEA SHC Task 41 experts [**Farkas et al. 2012**], ordered from most (top) to least (bottom) important based on number of first mentions in a survey among 79 professionals (similar number of engineers and architects) conducted by [**Prieto et al. 2017**].

Similarly, according to [**Azadian et al. 2013**], among the institutional, economic and technical barriers and acceptance and architectural considerations, the most important barriers to overcome are related to economic aspects and architectural considerations. Specific barriers to a large-scale deployment of BIPV, exposed in [**SolarPower Europe 2017**], relate to the electricity market rules, which do not foresee the incorporation of storage systems, to the ownership model regarding rental buildings, and to a lack of standards and safety rules.

Some of the barriers actually correspond to preconceived ideas that, although might have been true to some extent in the past, are nowadays obsolete given the extensive and fast-paced evolution of the PV sector. In Switzerland, Suisse Energie [**Suisse Energie 2018d**] provides answers and arguments to some questions and assumptions related to such preconceptions, e.g. Is there enough sun in Switzerland for solar energy? Solar installations are too expensive. Can I really consume the energy produced by my solar installation myself? Solar installations are not beautiful. However, the answers are directed to the general public and remain too general for a more specialised public such as architects.

We here below further describe some of the main barriers, along with related preconceived ideas and opportunities offered by BIPV.

Economic barriers, preconceptions and opportunities

As mentioned in [**Zanetti et al. 2017**], BIPV systems are commonly more expensive than BAPV, when limiting the comparison to the cost of the product itself. This is a misleading conclusion since BAPV and BIPV are incomparable products given that BIPV also fulfil constructive functions (water thingness, etc.) whereas BAPV systems do not. Apart from that difference, the cost should not be the unique criterion, since the economic efficiency should be calculated using parameters such as the Net Present Value (NPV), the payback time (PBT) or the Internal Rate of Return (IRR) considering the entire life of the project. According to [**Jad 2014**], the IRR of a standard renovation rarely exceeds 2%, whereas expectations are typically around 4% (as mentioned in Section 3.1.2). The potential for BIPV solutions to improve the cost-effectiveness in this context have been demonstrated by [**Bonomo et al. 2017**], where IRR values between 3-6% were obtained for different unitary-building-envelope BIPV solutions for façade and roofs.

BIPV could in fact theoretically produce on-site energy at an attractive and competitive price compared to the grid electricity cost [**Ballif et al. 2018**], mainly thanks to the double function that it offers. [**Passer et al. 2018**] highlights that the initial extra-cost of BIPV solution for façades, compared to a traditional construction material, is rapidly compensated (less than 10 years of payback time) by the on-site electricity produced and self-consumed or injected into the grid. In this sense, a complete approach based on the BIPV concept implies, among other things, to base the design of the installation and the entire renovation process on finding an equilibrium between self-consumption and self-sufficiency. This automatically leads to designing an installation that is well-adapted to the building.

Moreover, the perceived high cost of customised BIPV elements shall be overcome by considering the integration of such systems into prefabricated elements. In that way, BIPV can benefit from the advantages related to prefabrication, in which complete parts of the building are assembled in factory using manufacturing processes in continuous improvement, and where the use of standardised elements allows reaching much higher quality standards than what a classic construction on site allows.

In addition to the above-mentioned grid versus BIPV electricity cost competitiveness, on-site production offers a certain level of energy security in comparison to decentralised power supplies [**Kim et al. 2017**]. A BIPV energy source is largely unaffected from rising electricity costs and power outages caused by extreme events. This security of supply aspect is precisely one of the main objectives of the Energy Strategy 2050.

Another economic barrier relates to the rental law [**CFS 2018a**], introduced in Section 3.1.2 and which limits the rent increase following a renovation through a maximum profitability target. An emerging business model based on contracting can help overcome such financial barriers. PV performance contracting has had an increasingly significant impact on the solar market development [**Rickerson 2004**]. In this context, future applications and new business models to help the large-scale BIPV development in building renovation are presented in [**NCSC 2014**] through an Energy Services Performance Contracting (ESPC) approach offered by an Energy Services Company (ESCO). One of the greatest benefits of choosing this financial option is the division of the risk perceived by the owner or investor. The ESCO sells the electricity produced by the BIPV installation to the owners / tenants at a lower cost than the grid offers. The difference between the real production cost and the selling price, ESCO amortises the investment. This is a win-win model that could help to overcome financial and rental law related barriers.

BIPV within building codes and standards

The construction sector being one of the most traditional and conservative, there are no building codes regarding BIPV. This increases the perceived risks related to the use of cutting-edge technologies, for instance regarding technical aspects such as the mechanical stress and structural implications of PV modules, fire safety, and noise protection [**Yang 2015**]. One perceived risk relates to the proximity or contact of BIPV with traditional materials. According to experimental tests under real conditions on roofs and façades by [**Polo López et al. 2014**], current BIPV products can be used in retrofit projects without significant in terms of electric power due to the contact or proximity to other materials. [**Poulek et al. 2018**] have quantified the loss between BAPV and BIPV to be of less than 5%.

In an effort to clarify and harmonise the legislative framework on the integration of photovoltaic energy in buildings, the European standard EN 50583 - Photovoltaics in Buildings [**Erban 2016**] defines what are the specific rules to be taken into account when designing building envelopes using PV elements, both from a constructive (e.g. test of resistance, durability, safety) and electrical (e.g. dimensioned, safety, fire) point of view. Regarding BIPV specifically, an important aspect is related to the certification of BIPV products – i.e. guaranteeing their use as a building envelope element – for the construction industry. The EN 50583 standard states that to be considered as building-integrated, PV modules must replace a building component that provides a function as defined in the Construction Product Regulation (CPR) 305/2011 [**EU 2011**]. The constructive functions of BIPV taken into account are: weather protection (rain, snow, wind, hail, UV radiation), mechanical rigidity and structural integrity, thermal and solar protection (shading/daylighting).

Standards are therefore moving towards the standardisation of BIPV elements as new construction materials, safe, reliable and guaranteed. This will progressively reduce the risks perceived by the owners, architects and engineers and should reassure them at the moment of opting for this technology.

Another barrier lies in the idea that the lifespan of PV products is very short compared to other construction materials (e.g. traditional roof systems that are guaranteed for up to 15 years). However, the commercial warranties of PV products have the same range, between 10-15 years [**Zientara 2018**]. In addition, the manufacturer's linear performance warranty is of at least 25 years (with less than 0.8% of losses per year [**Phinikarides et al. 2014**]), much more than the 5 years warranty back in 1985 [**Jordan et al. 2013**]. Furthermore, as

[**Yang et al. 2016**] demonstrate through the analysis of existing installations, the lifespan of PV elements could be as long as 50 years.

In the framework of Active Interfaces research project, [**Martins et al. 2014**] conducted a study to increase the lifetime of BIPV elements and develop lightweight solutions to be applied in building renovation. Conducting a series of standard tests to check the durability and resistance of this new product allows to reassure the architect about viability and reliability of new BIPV materials [**Martins et al. 2016**]. For the moment, lifetime of innovative products is shorter than silicon-based technologies, making it difficult to use these emerging technologies like perovskite in real projects because they add uncertainties that are not well received by the architects or owners. In that sense, such products do not contribute at the moment to overcoming current barriers to a large-scale implementation of BIPV.

Many products but few good examples

As shown in previous sections, architects have access to a large number of available (and mature) products on the market, with high level of flexibility in terms of size and visual appearance (e.g. combining glass manufacturing techniques with the photovoltaics sector's know-how). However, architects still perceive most products as not adapted to the needs of the construction sector, seeing BIPV as a non-aesthetic add-on that imposes a technical difficulty to the design of building envelopes [**Ballif et al. 2018**].

Part of the problem possibly lies in the insufficient architecturally-oriented literature and product datasheets [**Farkas et al. 2012**], as well as the low number of aesthetically-convincing exemplary buildings [**Heinstein et al. 2013**]. Moreover, as mentioned, PV panels are often thought to unavoidably have a dark blue appearance with a shiny frame. This preconceived image of PV, despite having stayed true for some time, is now outdated given, among others, the customisation possibilities described in Section 3.2.2.

Acceptability issues

One of the architect's tasks involves the modernisation and upgrade of existing buildings while preserving and improving their architectural quality and dialogue with the built environment. As with any project of intervention in the built environment, one of the aspects to consider, especially in Switzerland, is the acceptability of the proposal by the planning commission and the inhabitants, who have the possibility to oppose the project. Architects must design strategies with BIPV where architectural quality can be guaranteed [**Hirschl 2005; Munari Probst et al. 2018**]. Undoubtedly, BIPV strategies will have formal and aesthetic consequences for the renovated building, but no more than in a classic renovation excluding BIPV. The use of BIPV should therefore not constitute an additional difficulty.

Availability and potential contribution of solar energy

Common myths about solar electricity concern the perceived insufficient space for PV on buildings for a significant production and contribution to a country's needs [**Garris 2009**]. This also relates to the misconception that only surfaces receiving more than 1'000 kWh/m^2·year of annual irradiation can be adequate for PV elements.

As highlighted in Chapter 1, the IEA has estimated the photovoltaic potential on building surfaces to be equivalent to 35% of the electricity consumption of Switzerland [**IEA 2002; OFEN 2018a**]. At the European scale, [**Defaix et al. 2012**] have estimated the BIPV potential on façades and roof of the building stock to represent about 950 GWp, allowing to produce 840 TWh/yr of electricity by 2030, corresponding to 22% of the expected annual electricity demand in Europe. These estimates demonstrate the non-negligible potential contribution of (BI)PV.

When defining where to position PV panels, a common approach is to select the surfaces by fixing a minimum annual irradiation threshold [**Costanzo et al. 2018**] to guarantee the cost-effectiveness of the PV installation. In general, it is not recommended to install PV panels on surfaces with less than 500 kWh/m^2·year of annual cumulative irradiation. Some guidelines such as [**Swissolar et al. 2018**] use, among others, the annual irradiation threshold as a parameter to evaluate the pertinence of PV installations, according to three cases: 1) favourable conditions for surfaces with >1'000 kWh/m^2·year, 2) appropriate conditions for surfaces with 1’000-800 kWh/m²·year, and 3) less or not appropriate conditions for surfaces with <800 kWh/m²·year. The intention of this type of guidelines is positive but remains too generalist. If an owner consults the solar cadastre or one of the proposed web-based tools such as **[OFEN et al. 2018]** to see the level of annual irradiation their building receives, most of the time they will have the impression that they only have the possibility to use the roof and that the rest of the envelope is not profitable and consequently not considered in the decision process.

The literature shows that there is a wide consensus around the adoption of the values suggested by [**Compagnon 2004**] for both façades (800 kWh/m²·year) and roofs (1’000 kWh/m²·year), which reflected the technological features of PV panels available on the market in 2004. However, this market, and the one of BIPV in particular, present a fast evolution in terms of efficiency improvement and decreasing prices, which renders too simplistic the approach of limiting the irradiation thresholds without taking into account all parameters involved in the renovation project. To reinforce this, as shown in **[Waibel et al. 2018]** the optimal placement of active elements on façade *“is not necessarily on surfaces with the highest cumulative annual irradiation […]”*. As highlighted earlier, and as will be demonstrated later on, cost-effectiveness can be achieved following a self-consumption approach which defies using a fixed irradiation threshold.

Opportunities for architects

Following an economic analysis over investment decisions for energy-efficiency renovation of multi-family houses involving a survey with 1’725 respondents, the **[CCEM 2012a]** stated: *“The study identifies architects as one of the most important sources of information for multi-family houses owners willing to perform a renovation”*. Architects are indeed the most influential stakeholders involved in the BIPV field as providers of new ideas to clients or contractors [**CCEM 2012a; Osseweijer et al. 2017**]. It is necessary that they understand and consider the possibilities, obligations, benefits and drawbacks of a BIPV project. If BIPV is properly considered from the early design phase, the architectural design can become the way to ensure a better PV integration from the formal, constructive, energetic and economic perspectives **[Munari Probst et al. 2012; Ballif et al. 2018]**.

[**Osseweijer et al. 2017**] notes that apart from architects as practitioners, universities and research centres have a key role in the development of BIPV. One example of this increasing interest in this field is the creation of new academic courses specifically focused on the integration of BIPV in the built environment, through an innovative and interdisciplinary curricula [**Sark et al. 2015**].

Although practitioners and researchers may exert a significant influence on practices, it is necessary that the underlying policies and economic conditions also be favourable for a widespread BIPV integration in renovation processes. Below are described the normative and financial initiatives applied in Switzerland to promote photovoltaics in buildings.

3.2.4. Promotion of photovoltaics in the Swiss context

Normative framework

The massive urban PV development is of interest to many of the local governments. Indeed, many cities are willing to develop PV, but face problems in finding the right way to start such a development. As a result, several initiatives are implemented to try to accelerate the introduction of PV installations in the built environment.

The latest Swiss Energy Law (LEne), in force since January 1, 2018 [**AFCF 2018**], marks a major turning point in the energy policy context. It aims at enabling the transition to an energy supply based on an increased share of renewable energy, particularly indigenous electricity generation through photovoltaics, and reducing by at least 43% the annual energy consumption per person by 2035. Specifically, with regard to photovoltaic energy, this law (Art. 15) obliges utility companies to accept locally produced energy for all installations of less than 3MWp. In terms of self-consumption (Art. 16), the law specifies that any PV operator may self-consume all or part of the energy produced on-site. They can also sell all or part of this energy for it to be consumed at the place of production. These two types of energy allocations are considered as self-consumption. In addition

(Art. 17), if several landowners who are end consumers share the same PV installation, they have the right to build a self-consumers' community (micro-grid). This self-consumption micro-grid will be treated as a single final consumer (Art. 18) through a single point of measurement.

Following modifications made to the Swiss Federal Law on Spatial Planning (LAT) **[AFCS 2016]** and its corresponding Ordinance on spatial planning (OAT) **[CFS 2016]**, solar energy in buildings is promoted and considered a priority. The LAT focuses on the concept of adapted PV installation on buildings, but in no case evokes the concept of integration, understood as a substitution of an element of construction. These documents state that no authorisation is required for solar installations that respect certain (aesthetical) integration criteria specified for non-protected buildings in terms of heritage. However, only rooftops are considered. Conversely, installations requiring an authorisation (e.g. those on façades) are subjected to public inquiry and hence to subjective acceptability criteria by the planning commission and the inhabitants themselves. These criteria and authorisations are further addressed in Section 3.3.

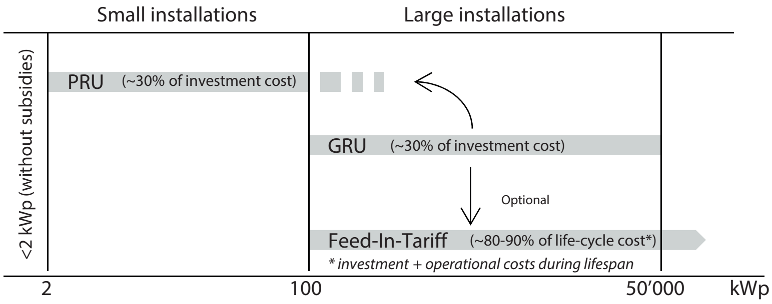
In reaction to the federal law, cantons and municipalities have also developed their policies. In the Canton of Neuchâtel, for instance, no authorisation is required to implement solar installations in buildings with a level of protection corresponding to category 2 (*"common"*) and 3 (*"unattractive"*). Unfortunately, no criteria have been set for integration based on the architectural features of the building. At the municipal level, despite not providing any specifications to integrate solar installations, the master plans of Neuchâtel define some protected viewpoints and classify the buildings according to the characteristics to be safeguarded (levels of protection). These analyses should be considered by architects (designers) when proposing different PV integration strategies in the renovation process.

Economic framework – initiatives

One of the most significant barriers which slows down the development of photovoltaic installations is usually the definition of the strategy of amortisation in economic terms.

In reaction to this, the first phase of implementation of the Energy Strategy 2050 in Switzerland is based on promoting the energy saving and increasing the renewables energy mainly through an incentive campaign **[CFS 2018b]** based on subventions **[OFEN 2018c]**. From 1 January 2018, a new subsidy named *"Retribution Unique (RU)"* or one-off payments (investment grants) appeared as a mechanism to promote PV installations. The Swiss Federal Office of Energy (*"Office fédéral de l'énergie"*; OFEN) proposes two options depending on the installation size **[OFEN 2018d]**: PRU – a RU for operators of small new photovoltaic installations between 2 kWp and 100 kWp, who are encouraged by this single payment that replaces the feed-in-tariff option (when injecting the overproduction onto the grid); and GRU – a RU for large photovoltaic installations between 100 kWp and 50 MWp, with the choice between the single payment and the payment of each kWh injected into the grid during a period of 15 years, named *"Système de Rétribution de l'Injection (SRI)"* **[OFEN 2018e]**. However, the SRI option is discouraged given the long waiting list, and it is therefore advisable to base calculations on the PRU and GRU aid equivalent to the 25-30% of the initial investment. Figure 3-18 presents a summary of the encouragement models for PV systems (installed after April 2018) according to their power and type.

The subsidies are allocated depending on the category of the installation (integrated or added / isolated), taking into account the highest investment for the BIPV installation and excluding the economic savings related to the fact that this installation substitutes some construction materials. In this way, BIPV installations are made more attractive as they are integrated in a process of renovation of the building envelope.



Type of installation	Fixed subsidy	< 30 kWp	≥ 30 kWp
	CHF	CHF/kWp	
BAPV	1’400	400	300
BIPV	1’600	460	340

Example (PRU) for **BIPV** installation with 57 kWp:
1’600 CHF + 460 CHF/kWp x 29.99 kWp + 340 CHF/kWp x (57.0 – 29.99) kWp = 24’579 CHF (TaxInc.)

Example (GRU) for **BAPV** installation with 182 kWp:
1’400 CHF + 400 CHF/kWp x 29.99 kWp + 300 CHF/kWp x (182 – 29.99) kWp = 58’999 CHF (TaxInc.)
With SRI option: Feed-In-Tariff about 0.11 CHF/kWh** (instead of GRU of 58’999 CHF)

** According to Feed-In-Tariff calculator (https://shkn.pronovo.ch/swissforms/TarifAuswahl.aspx)

Figure 3-18. Encouragement models for photovoltaic installations (from April 2018) according to their size and type (BA/BIPV) **[OFEN 2018c; pronovo 2018]**.

Apart from the public aids (PRU and GRU), each installation has, as mentioned, the right to inject the electricity overproduced (and not self-consumed) into the grid, agreeing a price with the supplier of the grid as provided by law **[OFEN 2018d]**. The feed-in-tariff in Switzerland (Figure 3-19) is defined by grid managers and is typically between 3.77 and 19.42 ctCHF/kWhe-pv (10.96 ctCHF/kWhe-pv in Neuchâtel in 2019) **[VESE 2018]**.

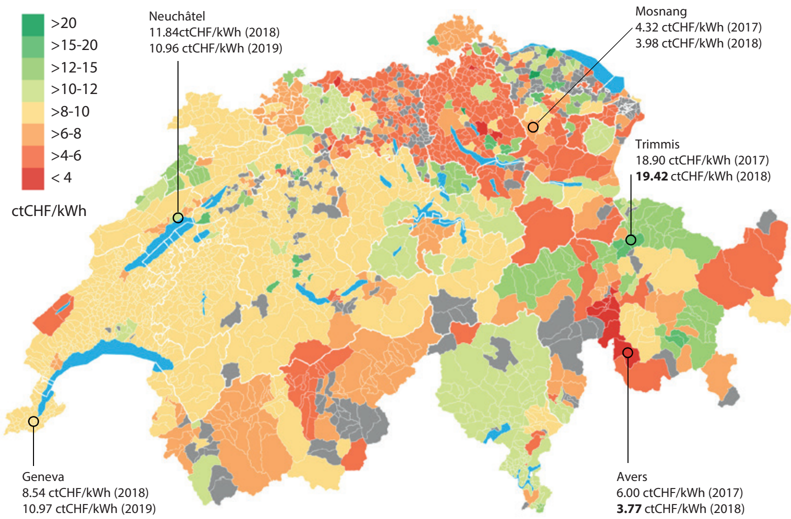


Figure 3-19. Feed-in-tariff through a colour-coded map in Switzerland for 2018 **[VESE 2018]**. Some extreme values for 2017-2019 are annotated for Geneva, Neuchâtel, Mosnang, Trimmis and Avers. Values are expressed in cents of Swiss franc per kWh injected into the grid (ctCHF/kWh) all taxes included.

In addition to the subventions and the feed-in tariffs, owners can benefit of tax reductions of 11-13% (considering an annual revenue of 100’000 CHF with a 25% tax rate) by investing in solar installations **[OFEN et al. 2018]**. Whatever type of subsidy chosen (PRU or GRU), owners can fully deduct the cost of investment in a PV system from the taxes **[HelionSolar 2018]**.

In addition, in Neuchâtel specifically, communal subsidies recently made available amount to 500 CHF/kWp with a maximum of 10’000 CHF per installation **[Ville de Neuchâtel 2018]**.

As mentioned, subsidies will be reduced in the near future **[OFEN 2018d]** since further development of PV technologies is expected to cause a reduction in the cost of BIPV, as it becomes a standard technology accessible and available on the market. Specifically, the *“Système de Rétribution de l’Injection”* expires in 2024 and one-off payments (PRU, GRU) will remain in force until 2031.

In the second phase of the implementation of the Energy Strategy 2050, the type of incentive is expected to change. Climate or energy taxes according to the CO_2 emissions are likely to be introduced, replacing the subsidy system provided by the first phase (see also evolution of CO_2 taxes in Section 3.1.3) [**Yale et al. 2017**].

3.2.5. Towards an architecturally-driven multi-criteria methodology for defining BIPV in renovation

The BIPV concept has evolved along the years to encompass a wider range of features. Initially, BIPV was thought of as an indivisible part of the building envelope with a dual function, substituting a conventional/inert material and producing electricity to be injected into the grid. Then, requirements in terms of integration and sizing with respect to the operational needs of the building were added, with the self-sufficiency and self-consumption concepts, to solve grid-injection incompatibilities and increase cost-effectiveness. Recent literature focusing on building renovation highlight the importance of a SC and SS approach in the BIPV sizing and design, along with LCA and LCC evaluations towards a better environmental performance. Moreover, architectural integration has become central – and possible by means of emerging customisation techniques – to enhance the acceptance of BIPV particularly on façades.

Although existing catalogues and databases offer classifications of (BI)PV products, namely according to the part of the building on which the products can be installed, they do not show all constructive characteristics that could help architects to design the thermal envelope using BIPV. In general, they also do not show what could be the architectural formal result or how these products could be adapted to different architectural situations.

Moreover, despite important European research projects aiming to promote a large-scale implementation of new BIPV products in the building stock [**Engström 2005; EC 2018b, 2018c, 2018d; Onyxsolar 2018b**], there remains a lack of architectural approaches in renovation project of residential buildings and of holistic methods to assess BIPV to support the design process.

As highlighted in [**SolarPower Europe 2017**], in 2016 more than 60% of solar systems on buildings in Europe are roof installations, and this dominance is expected to continue despite the great potential provided by the façades. This is mainly due to a lack of renovation studies using façades as available surfaces for BIPV installations, and few technically and aesthetically convincing integration examples of residential buildings in urban settings [**IEE 2006**]. With only 10% of the PV market in Switzerland belonging to the residential sector, it is necessary to further focus on promoting the use of this technology in residential buildings [**SolarPower Europe 2017**], which represent 70% of the total building stock (see Section 3.1.1). In such buildings, the use of façades is indeed crucial to increase the global performance of BIPV installations, e.g. through higher self-consumption of the electricity produced by the building itself [**Couty et al. 2017**].

The renovation process of buildings represents a great opportunity to integrate photovoltaics into the building envelope, strategy that can help to improve the economic feasibility or cost-effectiveness of the whole renovation project by increasing the NPV and IRR and decreasing the payback period compared to an energy renovation without BIPV strategies.

In light of the state of the art presented in this section, it appears essential to further investigate the concept of BIPV in renovation through a holistic, architectural-design oriented and multi-criteria approach. The following section covers the literature regarding the assessment methods and tools that exist to support the design, sizing, and evaluation of BIPV strategies according to various criteria including qualitative (e.g. acceptability) and quantitative aspects (e.g. environmental impact).

3.3. Assessment methods and tools

In this section, a review of the literature regarding the different assessment methods, approaches and tools used for solar integration in the building sector is presented, with a focus on renovation projects. This section is divided in two parts: the first one focuses on approaches related to the acceptability of projects integrating solar energy, while the second part reviews methods and tools for the sizing of PV systems and their evaluation in terms of different indicators such as environmental impact.

3.3.1. Acceptability-related methods and tools

Various types of instruments exist to help better integrate PV products in building envelopes, often with a focus on the visual impact as a key factor to address towards improving acceptability [**Zanetti et al. 2010**]. We here review some of these instruments, which are meant to support the early planning and design stage of PV projects.

Guidelines

Usually, public authorities in Switzerland rely on PV integration guidelines to determine whether a formal procedure for requesting an authorisation or construction permit is necessary for a given project. It is through these guidelines that municipalities control the integration quality of solar systems [**SUPSI 2018**].

While a first set of guidelines are defined at the federal level through the LAT/OAT, each canton also establishes their own list of conditions. Based on the OAT, if the following conditions – assumed to guarantee a sufficiently adapted roof installation – are respected, there is no need to undertake any authorisation procedures [**OAT 2014**]: a) they do not exceed the sides of the roof perpendicularly by more than 20 cm, b) they do not protrude from the roof, when viewed from the front and from above, c) they have a low reflectivity according to the state technical knowledge, and d) they constitute an integral surface.

The guidelines from the cantons of Bern, Thurgau and Wettingen focus on PV installations on roofs, showing different examples on farm buildings [**SUPSI 2018**]. The guidelines of Zurich, also dealing with roof installations, show where it is potentially possible to install PV elements, but does not show good examples of integration. The guidelines of Ticino show just a few examples of BAPV and BIPV on roofs, substituting traditional tiles by standard PV modules.

The guidelines in the French-speaking cantons, published by the Conférence Romande des Délégués à l'Energie (CRDE), offer some recommendations for the solar integration in architecture. However, they also only focus on roofs and on how to make the PV installation more harmonious / invisible with respect to the characteristics of traditional buildings. Recommendations include **[CRDE 2007; SMS 2013]**:

- Group all the PV panels together to avoid as much as possible the dispersion of panels.
- Embed the panels in the roof, as a solar installation built into the roof or barely protruding is hardly noticeable, it blends in.
- Give the panel a rectangular shape, since a panel of the same shape as another part of the building fits better with the whole.
- Respect the contours of the building, in terms of aesthetics, it is important not to *"overflow"* with respect to the building contour.
- Ensure the parallelism of plans and lines, so as PV panels have the same orientation and inclination as the edges and the sides of the roof and façades.
- On flat roof, place the PV panels further back from the edge and do not exceed 120 cm high.
- Match the colours; if the colour of the frame matches the rest of the building, the PV panels will not be perceived as a foreign object.

Whereas the above guidelines concern only roof installations, recommendations have been made by other entities for PV systems on both roof and façades.

In the framework of the IEA SHC Task 41, aesthetics-related integration criteria were defined, as conditions for ensuring coherence of solar installations with the whole building [**Frontini et al. 2012a**]. The four criteria proposed are that: 1) the position and dimension of the modules must be coherent with the architectural composition of the whole building; 2) the installation's visible material(s), surface texture(s) and colour(s) should be compatible with the other building skin materials, colours and textures with which they interact; 3) module size and shape must be compatible with the building composition and the various dimensions of the other façade elements; and 4) joint types must be carefully considered when choosing the product.

The literature shows that there is a general consensus on the fact that the visual acceptability of a type of integration depends on the sensitivity of the building it refers to [**Lucchi et al. 2014**] and its surrounding area [**Bahjejian 2011; Munari Probst et al. 2018**]. Different methods have been used in the literature to assess this sensitivity, either based on a heritage protection database [**Lucchi et al. 2014**], or on the type of urban area [**Munari Probst et al. 2018**]. The next section introduces methods that focus on evaluating the visibility of solar systems in relation with the sensitivity of the context.

Visibility-based assessment methods

Arguing that it is possible to conduct solar integration in *"delicate contexts"*, e.g. with a high level of heritage protection, [**Munari Probst et al. 2015**] proposed the LESO-QSV (Quality – Site – Visibility) method, which is based on the concept of the *"architectural criticity of city surfaces"*. This criticity indicates the level of integration quality required in a given context and is defined by the system visibility – composed of remote and close visibility from the public domain as seen in Figure 3-20 – and by the context sensitivity – related to the urban context where the building is situated. Crossing the three possible levels of visibility and sensitivity as seen in the left-side image of Figure 3-21 results in nine situations for which quality expectations must be defined. In parallel, the system's features that affect the integration quality – geometry, materiality, and modular pattern – are assessed on a coherence scale (right-side image in Figure 3-21).

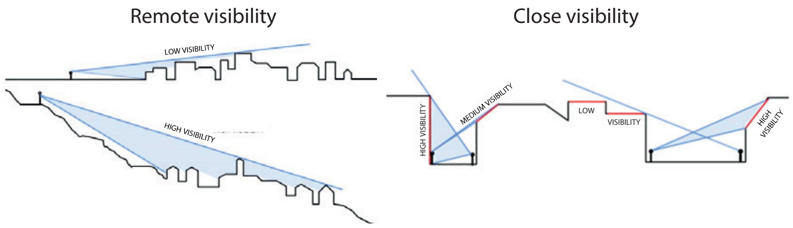


Figure 3-20. Assessment of the system's remote (left) and close (right) visibility in the LESO-QSV approach [**Munari Probst et al. 2015**].

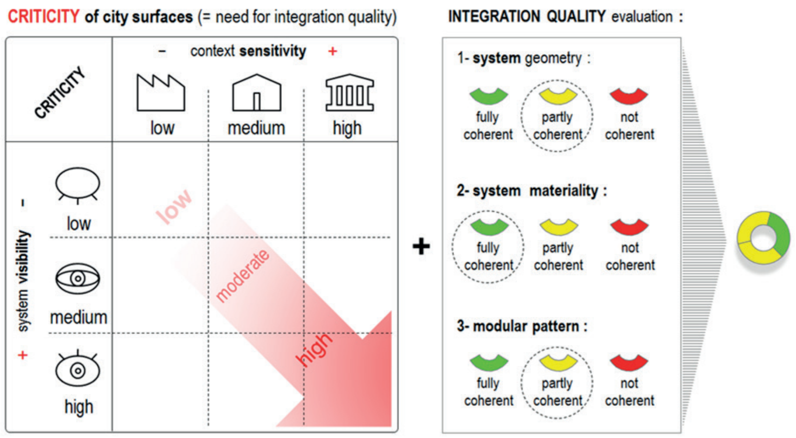


Figure 3-21. Evaluation of criticity (left) and integration quality evaluation (right) in the LESO-QSV approach [**Munari Probst et al. 2018**].

The LESO-QSV tools may provide a common framework upon which authorities and the urban commission in charge of evaluating a project can base their process and decisions. Indeed, the application of this kind of method may help authorities establish integration quality expectations and stakeholders define integration strategies. However, although the approach aims at providing objective answers to the debate on solar systems acceptability, subjectivity remains within the process of defining the level of criticity and integration quality. Moreover, the approach supports the idea that solar products are by default disturbing, implying a priori that PV panels are considered an architectural nuisance. This may hold for classical dark-blue PV panels, particularly on façades (most visible surfaces from public spaces) and sloped roofs, particularly in areas presenting a topography of varying altitude, which is typical of many Swiss cities. However, the diversity of available products as previously illustrated now offers unprecedented possibilities for architectural composition and integration.

Building upon the LESO-QSV approach, [**Florio 2018**] developed a visibility assessment method based on a visibility index whose definition varies according to the scale of application (e.g. district vs building roof). Using quantitative indicators capturing geometrical, physical and psycho-physiological aspects, the study concludes that *"stakeholders can reasonably expect to produce a serious amount of solar energy by the way of building integrated solar modules without crucially affecting public perception"*.

Another quantitative method was proposed by **[Xu 2016]** to quantify the probability of a BIPV installation to attract the human visual attention. By processing renderings using the saliency method coming from the field of computer vision, quantitative descriptors of the image (e.g. pixel colour and intensity) are used to produce saliency maps. As such, the level of perturbation of a solar installation on building façades is assessed by how much the installation differs from the original building façade in terms of aspects that attract visual attention. Despite being an objective approach, the descriptors used are subject to personal preferences. Moreover, once again, the underlying principle remains the minimisation of the visual impact with respect to the original building's image. This method is also complicated to use in the daily practice of architectural designers.

Survey

Insights into the acceptance of PV projects can be gained through surveys, a technique used in a recent doctoral research where a qualitative survey was filed by 500 Swiss homeowners [**Curtius 2018**]. The survey, concerning PV roof integration, was conducted to highlight factors that influence the adoption of solar systems in the built environment, focusing on the role of the most important stakeholders (including architects, installers, owners, real estate developers, manufacturers, policy makers and neighbours). The study shows that the colour and origin (preferring locally manufacturing products) of the BIPV elements are the main drivers for an increasing share of preference for BIPV. Results also show that 85% of owners are considering to install PV and are willing to pay 22% more for better architecturally-integrated panels (red or black colours) instead of installing a non-integrated PV system (e.g. rack-mounted PV installation using blue PV panels). Despite economic factors being key, this survey *"suggests a trend towards valuing non-monetised properties rather than a pure return on investment"* [**Ballif et al. 2018**].

3.3.2. Sizing and evaluation methods and tools

This section presents a review of methods and tools allowing to conduct various analyses with a focus on photovoltaic and energy performance of existing buildings.

As argued in Section 3.2, addressing the concept of BIPV in renovation requires a multi-criteria approach to capture, in addition to the above-mentioned architectural integration facet, all relevant features from the economic to the environmental impact aspects. Table 3-11 presents a non-exhaustive list of methods and tools that can be used in the context of renovation and/or (BI)PV, to support one or many of the steps from a preliminary assessment of the solar potential to a full life-cycle assessment of a PV-integrating building renovation.

To date, there is to our knowledge no holistic and operational method for the renewal of buildings that can be used to define improvement strategies with BIPV, and assess the impact of such strategies within the entire renovation process in terms of level of integration, economic, technical and environmental balance. To do such a multi-criteria assessment requires resorting to multiple tools, such as those introduced in the following paragraphs.

A preliminary assessment of the solar potential at a scale and resolution that can range from a city, modelled at a low level of detail, down to a detailed building surface, is a typical first step in a project involving solar energy.

Tools that estimate the solar potential based on the amount of exposed building envelope surfaces and their level of exposure in terms of solar irradiation include web-based solar cadastres (or maps), such as the Swiss solar cadastre [**Swisstopo 2018**], as well as programs that calculate the solar radiation received by building surfaces (e.g. Heliodon [**Beckers et al. 2011**], DIVA-for-Rhino [**Solemma LCC 2018**]). The main advantages of such tools lie in their simplicity and rapidity of use and clear 2D and 3D visualisations.

Method / tool	Renovation scenarios	Economic calculations	Final energy balance	Performance certification	LCA	PV potential / production	Comparison with energy targets	Objective / example tools
Solar cadastre-based tools								Estimate the annual production potential on building surfaces
						(*)		- **Swiss solar cadastre** [Swisstopo 2018]
		(*)	(-)			(*)		- **Solar calculator webtool** [OFEN *et al.* 2018]
		(*)				(*)		- **Geneva solar cadastre** [Desthieux *et al.* 2018]
Solar irradiation tools								Support tool for solar design in architecture
						(*)		- **Heliodon** [Beckers *et al.* 2011]
						*		- **DIVA** / **Radiance** [Solemma LCC 2018]
PV specific tools								PV systems sizing, production and economic assessment of photovoltaics installations
			(-)			(*)		- **PVopti** [Minergie *et al.* 2018]
		*						- **PV installation cost calculator** [Swissolar 2018]
		*				*		- **PV-Syst** software [PVsyst SA 2018]
Environmental impact data-based tools								Provide reference data for LCA calculation
	(-)							- **KBOB** / **Ecoinvent** database [xxx]
			(-)		*	(-)		- **ECO-BAT** software [Favre *et al.* 2016]
Renovation cost analysis tools								Cost-effectiveness evaluation
	*	*						- **EPIQR**+ software [EPIQR Réenovation sàrl 2004]
	*	*			(*)	(-)		- **INSPIRE Tool** [Suisse Energie 2018b]
Building performance simulation tools								Detailed building performance evaluations and analysis
	*		*	*	(*)	(*)	*	- **LESOSAI** software [E4tech 2018]
	*	(*)	*	*	(*)	*		- **DesignBuilder** software [DesignBuilder 2018]

(*) Studied at low level of detail (LoD) or in a simplified manner
(-) Considered but not calculated within/by the tool itself / default values from database

Table 3-11. Review and comparison between different existing methods and assessment tools related to renovation and PV installations in the Swiss context.

More detailed information can be obtained through advanced PV-specific tools such as PV-Syst [**PVsyst SA 2018**], which takes into account all technical aspects of photovoltaic (cells, panels, grid connection type, wiring, inverters, etc.) and has a very comprehensive database of existing products. PV-Syst allows calculating at two levels of detail (1) simplified method for the early-design phase and (2) detailed method where it is possible to create a 3D model to take into account the surrounding built environment. The updated database represents a good reference to obtain the specific features of existing commercial products. However, using this tool requires some level of expertise and no information is provided on the constructive aspects that could help architects use BIPV as a construction material.

When detailed information on the system to install is known (e.g. nominal installed power, initial investment, etc.), the Excel-based PV installation cost calculator [**Swissolar 2018**] can be used to verify the financial viability of the installation. Information on the cost and payback time can also be obtained from some solar cadastre-based tools such as the Geneva solar cadastre [**Desthieux et al. 2018**] and the solar calculator online tool [**OFEN et al. 2018**]. The latter does a preliminary estimation of how much energy could be produced on the roof and/or façades based on the above-mentioned Swiss solar cadastre data [**Swisstopo 2018**] (see Figure 3-22), and conducts an economic calculation to give the building owner an idea about the payback time based on the investment and the subsidies that could be received (see Figure 3-23).

As can be seen in Figure 3-22 for the selected façade example, the solar cadastre categorises the evaluated surface as having a PV potential that ranges from *"low"* to *"excellent"*. This assessment is based on the irradiation levels shown in Table 3-12 **[Klauser 2016]**. These values are similar to those found in [**Swissolar et al. 2018**], where both roof and façade surfaces receiving less than 800 kWh/m^2·yr are badly rated, and those suggested by [**Compagnon 2004**], which are of 800 kWh/m^2·yr for façades and 1'000 kWh/m^2·yr for roofs. Relying on irradiation threshold values for selecting the most adequate surfaces for PV represents a relatively simple and commonly used guideline or rule-of-thumb. Yet, as argued in Section 3.2.3, this approach is general (as in not case-specific) and threshold values are typically derived from economic considerations and should therefore be frequently updated given the rapid price changes.

More comprehensive methods to select surfaces that should be made active include optimisation-based approaches using one or multiple objective functions such as the PV production (to maximise) and the cost (to minimise) [**Youssef et al. 2016, 2018; Martín-Chivelet et al. 2017; Waibel et al. 2018**]. Depending on the methods' functioning, they risk not being adapted to BIPV application on existing façades when the results lead to an unrealistic repartition of the active surfaces from an operational point of view [**Attia et al. 2009; Østergård et al. 2016**]. They are also often time-consuming and complex to the point where architects / designers are likely to not feel comfortable using them.

Regardless of the technique used, and as discussed in Section 3.2.3, aiming at balancing the self-consumption (SC) and self-sufficiency (SS) ratios may be the most appropriate strategy for renovation projects with BIPV. To calculate the SC and SS, information on the building's needs is essential.

Table 3-12. Irradiation values used to assess the PV-suitability of a given building surface in the Swiss solar cadastre [**Klauser 2016; Swisstopo 2018**].

PV potential assessment	Roof threshold (kWh/m^2·yr)	Façade threshold (kWh/m^2·yr)
Low	< 800	< 600
Medium	≥ 800 and < 1'000	≥ 600 and < 800
Good	≥ 1'000 and < 1'200	≥ 800 and < 1'000
Very good	≥ 1'200 and < 1'400	≥ 1'000 and < 1'200
Excellent	≥ 1'400	≥ 1'200

The above-mentioned online solar calculator [**OFEN et al. 2018**] does take into account some information on the building itself. For instance, the user has the possibility of specifying the number of inhabitants, the year the building was constructed, and the type of heating system. This information is used to estimate the building's needs and subsequently the amount of produced energy that can be consumed by the building itself (SC ratio).

Figure 3-22. Solar potential estimation on a façade by the Swiss solar cadastre **[Swisstopo 2018]**.

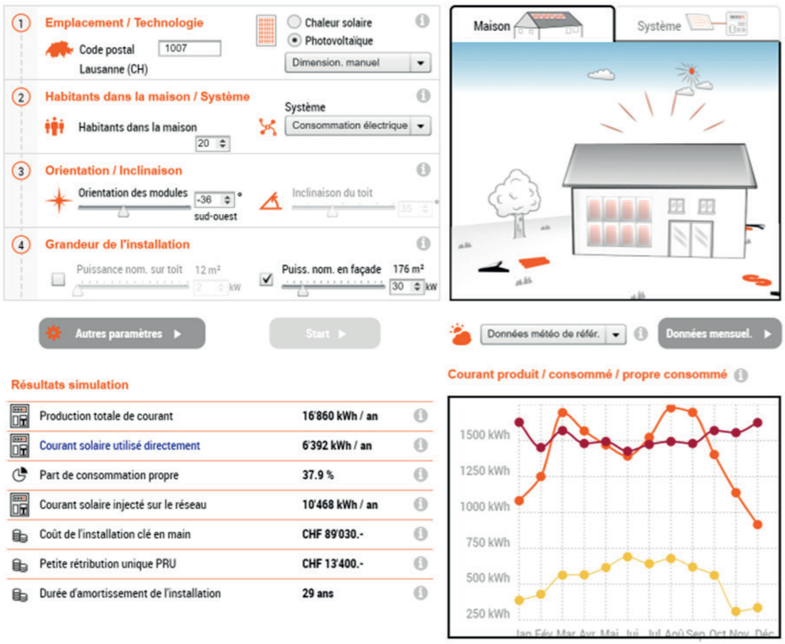


Figure 3-23. Solar production estimation and financial analysis for a façade-mounted system by the solar calculator webtool **[OFEN et al. 2018]**.

This sort of information on the amount of energy that can be self-consumed versus exported to / imported from the grid is also provided by the Excel-based PVopti **[Minergie et al. 2018]**, developed by Minergie®. However, this tool does not estimate the building's needs, but rather asks the user to provide this information (i.e. annual or monthly heating needs) as an input. It then converts or redistributes this data on an hourly-basis to do an energy balance (or load matching) before returning the annual and monthly energy needs (for heating, ventilation, etc.) and production. From this data, the SC and the SS are computed and shown to the user.

In the context of renovation, it is essential not only to consider both the potential PV production and the building's needs, but to do so in a detailed manner where BIPV-system sizing and design as well as the expected post-renovation building's needs are fully integrated and interconnected. This requires resorting to advanced building performance simulation (BPS) tools where BIPV-integrating renovation strategies can be described and assessed. This is made possible by BPS tools that allow defining and separately configuring any parameter such as HVAC system, window glazing type, wall insulation, etc.

According to **[Clarke et al. 2015]**, when integrated in the design process, BPS tools have an increasing role in assisting with the design of energy efficient habitats towards achieving the 2050 targets, contributing at the same time to increase the knowledge in the adoption of the right strategies. Similarly, discussing the use of building simulations to support decision making during the design process, **[Østergård et al. 2016]** highlight the need for improved interoperability between computer-aided design (CAD) – widely used by architects – and BPS software.

Although not BPS tools, EPIQR+ **[Flourentzos et al. 2000; EPIQR Réenovation sàrl 2004]** and INSPIRE Tool **[Jakob et al. 2014]** can be used to define renovation strategies and assess their effectiveness in terms of cost and energy efficiency. Their main evaluation criteria are related to economic aspects and energy balance (usually used to justify that the project meets the requirements of existing regulations). However, these tools do not offer the possibility to include PV-system strategies.

In the Swiss context, **[Wang et al. 2018]** developed the Combined Energy Simulation And Retrofitting (CESAR) tool, which takes information from SIA norms to set the internal conditions and uses EnergyPlus **[Crawley et al. 2001]** (with Matlab **[MathWorks 2018]**) as the energy simulation software to obtain the hourly heating demand. This tool focuses on simulation with a low-level of detail and implements only current practice renovation strategies that prevent achieving the 2050 targets. The outputs are quite complete, including final energy consumption and environmental impacts of retrofit measures. However, there is no possibility to implement BIPV strategies or define architectural design targets.

More comprehensive is the LESOSAI software, a BPS tool for the certification and thermal balance calculation of buildings, which supports a multi-criteria evaluation with the possibility of introducing different renovation strategies (to comply with a chosen energy requirement e.g. SIA 380/1:2016 or Minergie® label) **[Favre et al. 2010]**. The tool offers the option to incorporate photovoltaic energy production, but with no architectural criteria considerations. Moreover, it does not consider economic aspects and it is not possible to propose a detailed PV installation in the building envelope. It also remains limited in terms of the level of detail that can be reached both in the 3D modelling of the building as well as in its parametric configuration (e.g. regarding advanced parameters such as HVAC system characteristics and envelope air tightness).

DesignBuilder **[DesignBuilder 2018]**, a BPS tool consisting in a user-interface to the widely used EnergyPlus simulation engine **[Crawley et al. 2001]**, remediates to these shortcomings by allowing to reach a higher level of detail in the building modelling and parametric description. Dynamic hourly simulation provides energy demand and consumption profiles as well as (BI)PV production values.

To deepen the evaluation of a project, an assessment should be made on the whole life of the building, including its construction, operational and deconstruction phases. This life-cycle assessment (LCA) is essential to consider the environmental impacts of a building and be able to verify its compliance with the 2'000-Watt Society targets.

[Hollberg et al. 2016] highlight the importance of conducting an LCA from the early design stage using parametric models and tools, notably to allow architects to focus on design tasks and decrease the cost of design changes. Through a parametric approach, it is possible to identify the influence of each design decision and their impact on the final energy performance.

The LCA methodology for buildings, described in the European standard EN 15978 **[ECS 2011]**, decomposes the building's life-cycle stages into four main phases as illustrated in Figure 3-24. To each stage corresponds a set of information necessary to conduct the LCA evaluation, including product-specific information (product stage) and building-specific data (e.g. operational energy use). A fundamental requirement for LCA is thus the access to data regarding the environmental impact associated to each building element (materials' and systems' embodied impacts) as well as each energy source used for the operation of the building (e.g. impact of electricity from the grid used for artificial lighting). This data is intrinsically context-specific; it depends for instance on the origin of the materials used in a given project, as well as on the specific energy mix from the country's grid. The accuracy of the environmental impact data is a topic recurrently highlighted in the literature **[Dixit et al. 2012]**.

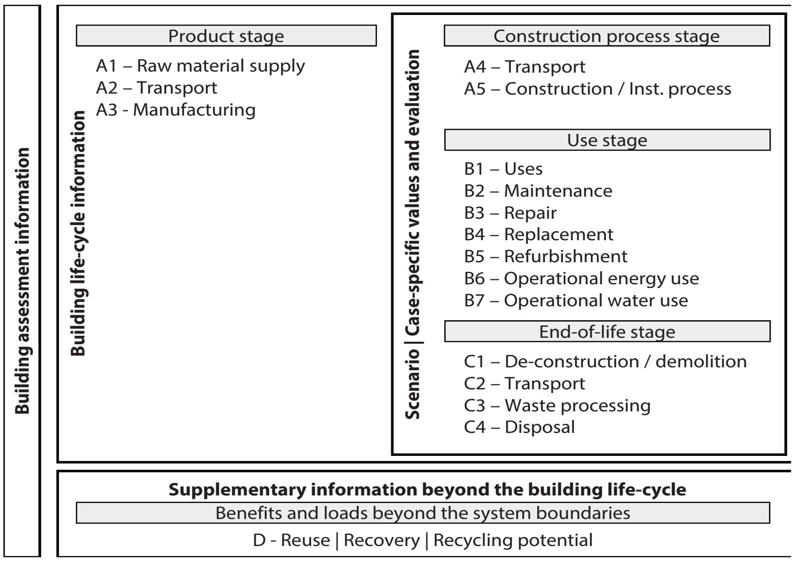


Figure 3-24. Stages in the building life-cycle assessment according to the European standard EN 15978 **[ECS 2011]**, indicating where and which type of information is necessary to conduct the LCA.

Among the different indicators that can be used to describe and quantify environmental impacts and resource use **[ECS 2011]**, the three common ones often adopted in a (simple or partial) building LCA are **[UNEP et al. 2009; Gustavsson et al. 2010; SIA 2017b]**:

- Global warming potential (GWP) or Greenhouse gas (GHG) emissions, expressed in kg of CO_2 equivalent
- Cumulative energy demand (CED) or primary energy related to resources including those used as raw material and quantified in MJ or kWh
- Cumulative energy demand, non-renewable (CEDnr) or non-renewable portion of the primary energy related to resources including those used as raw material and quantified in MJ or kWh

Various instruments exist to support conducting an LCA in the Swiss context, starting with databases of environmental impact data for construction components and systems. Environmental impact factors including those for the GWP, CED and CEDnr related to construction materials, systems and equipment, energy sources and more are provided in the KBOB database of LCA data in the construction sector **[KBOB 2016]**, which is adapted from the Ecoinvent database (that extends beyond the building sector) **[ecoinvent 2018]**. With respect to the EN 15798 building stages, KBOB data ignore phases A4 – transport to the construction site – and A5 – energy and emissions related to the construction-installation process – since these are case-specific (e.g. dependent upon the building's location).

To accompany the SIA 2040 document **[SIA 2018]**, an Excel-based tool exists to obtain a first estimate of the GWP and CEDnr values for a project related to the construction (embodied energy and emissions of materials and systems), operational, and building-induced mobility domains **[Suisse Energie 2018f]**. The user must first provide information on the building (e.g. surface of foundations, external walls, windows, balconies, etc., energy need and type of systems), and the tool uses default values and data from SIA norms **[SIA 2010, 2016a, 2016d]** and the KBOB database **[KBOB 2016]** to estimate the environmental performance.

The ECO-BAT software **[Favre et al. 2016]**, dedicated to conducting a simple LCA in the Swiss context, exploits the KBOB database and allows adding the energy and emissions related to the transport of materials to the building site (A4). However, ECO-BAT does not perform any evaluation of the building operational energy consumption, which must thus be provided by the user as input data to be included in the LCA, along with detailed information on each construction layer material and all active systems.

LESOSAI **[Favre et al. 2010]**, in addition to also offering the possibility of conducting a simplified LCA using the KBOB database, does include operational energy simulation. DesignBuilder **[DesignBuilder 2018]** redirects the user to the One Click LCA online tool **[Bionova Ltd. 2015]** that takes as input a gbXML file exported from DesignBuilder. One Click LCA then runs the LCA using data from the relevant country-specific data out of its extensive coverage, which is once again the KBOB database for Switzerland.

To assess the performance of a (BI)PV installation specifically (as opposed to the whole building), **[Ng et al. 2014]** recommends to use the GHG emissions (kgCO2eq/kWhe-pv) and CEDnr (MJ/kWhe-pv) intensity of photovoltaic electricity, along with the energy payback time (EPBT; years) and energy return on energy investment (EROEI; kWhNRE-pv/kWhCEDnr), which are both calculated from the CEDnr.

The EPBT and its equivalent in terms of GHG emissions (greenhouse-gas payback time; GPBT) were calculated in some studies for BAPV and BIPV installations. For instance, an EPBT (respectively GPBT) of 7.3 (5.2) years was estimated for a roof BIPV in Hong Kong **[Lu et al. 2010]**, while these values were found to be of 3.1 and 4.2 years (0.4 and 1.3 years) respectively for a BIPV and BAPV example in Shanghai **[Wang et al. 2016]**. In another study over different roof-mounted BIPV systems across various regions in China, EPBT values ranging between 3 and 7.4 years where obtained **[Huang et al. 2017]**. These estimates are well below the expected lifetime of BIPV products (at least 25 years **[Yang et al. 2016; NREL 2018]**), but it is important to highlight that the assessed PV installations are generally on roof, south-facing with an optimal inclination that maximise the energy production. Moreover, the comparison is made with grid-electricity produced mainly with coal (Chinese context) and therefore with high GHG emissions compared to PV electricity.

Similarly, a study made in the context of the Netherlands also showed short EPBTs for BIPV rooftop designs, from 4.3 years based on the current situation where the grid efficiency (average primary energy to electricity conversion efficiency at the demand side) is of 44.5%, to an EPBT of 2 years considering an optimistic future scenario where the grid efficiency would have increased to 72.5% along with improvements in the PV module efficiency (from 14.8 to 27.6) and lower environmental impacts **[Ritzen et al. 2017]**.

With the rapid evolution of photovoltaic technology and products, it is difficult to find the updated data necessary to conduct LCA of PV installations. A recent publication by **[Ludin et al. 2018]** reviewed and summarised LCA studies on PV technologies, looking at the evolution of environmental impacts from the Ecoinvent database **[ecoinvent 2018]** and real case studies. Although only rooftop and ground-mounted systems are studied with partial / incomplete information available, out of the Swiss studies reviewed **[Dones et al. 1998; Jungbluth 2005; Jungbluth et al. 2007]**, the GWP of PV installations decreased from 0.114 (in 1998) to 0.078 (in 2015) $kgCO_2$/kWhpv-e (with the mean annual irradiation being of 1'117 kWh/m^2·year in Switzerland).

In a study on a rooftop BIPV in the Netherlands, **[Ritzen et al. 2017]** compared the actual situation to three defined future scenarios with distinct primary energy impact factors, PV module, and grid efficiency. While the current primary energy factors are of 3060-4070 MJ/m^2 (of PV area) depending on the tool / database (SimaPro versus ICE), the business-as-usual (BAU) scenario was defined with values between 2488-3309 MJ/m^2, and the most optimistic scenario with values between 1346-1791 MJ/m^2. For comparison, the LCA data currently provided by Ecoinvent **[ecoinvent 2018]** and the ECO-BAT software **[Favre et al. 2016]** are between 2347 and 2725 MJ/m^2 depending on the technology and system (mounted on wall, flat or slopped roof), thus similar to the BAU scenario.

In addition to assessing environmental impacts, the cost-effectiveness of BIPV-integrating renovation strategies can be verified through a life-cycle cost (LCC) approach using the Discounted-Cash flow (DCF) method **[Roger W et al. 2007]**.

This type of approach is recommended by the SIA 480:2016 standard on the cost-effectiveness of investments in buildings **[SIA 2016c]**, which highlights the importance of conducting an economical evaluation (in addition to considering all other parameters such as comfort, aesthetics, security, social impact an ecology). The standard encourages using the DCF method with the Internal Rate of Return (IRR) and Net Present Value (NPV) as main indicators.

The INSPIRE Tool **[Jakob 2006; Econcept AG 2018]** introduced earlier uses the DCF method through the cost-optimal methodology **[BPIE 2010]**.

The data necessary to conduct an economic analysis include prices of all building components including BIPV systems as well as energy prices and economic parameters (e.g. interest rate). For the Swiss context, complementary reference databases of prices of construction elements are published in **[CRB 2012a, 2012b, 2012c, OFS 2014, 2015b]**. The Batilog Devis software **[BEC Partners SA 2018]** makes use of all these databases.

As for environmental impact data, there is a lack of detailed data on BIPV costs. A market study conducted by the Swiss Federal Office of Energy in 2016 can be used as a basis [**OFEN et al. 2018**]. The data it provides is consistent with more recent cost databases published in [**Fischer 2018; ITRPV 2018**].

3.4. Synthesis

The literature review shows that is a lack of holistic approaches for addressing renovation projects of residential buildings integrating BIPV, where the term integration is to be understood in all of its meanings. That is to say, not only from a construction / functional point of view, but also in terms of coherence with the building architecture, its context, its energy needs, as well as in terms of environmental and economic implications. In this context, the expected contributions of the thesis are synthesised as follows:

- Put to light the residential building stock, linking the urban and building scales through an archetype approach;
- Investigate and demonstrate the kind of renovation strategies needed to achieve the Swiss objectives for 2050, by integrating passive, active, and BIPV strategies;
- Demonstrate the importance of taking advantage of the energy renovation process to integrate photovoltaic energy;
- Verify the level of performance that can be reached by current practice and demonstrate the need to overcome the inertia of current practice;
- Demystify certain preconceived ideas such as that:
  - BIPV is not economically justifiable, by verifying the cost-effectiveness through a life-cycle cost (LCC) analysis;
  - PV panels are an architectural nuisance, by starting from the principle that through case studies, we can develop a new architectural language incorporating BIPV based on different levels of interventions, where visible products are made part of the envelope, thus contributing to the architectural expression of the building;
- Investigate the role of BIPV in renovation from a multi-criteria point of view, to see how the BIPV concept can be extended beyond what has been defined up to now;
- Promote renovation among investors and put in evidence new business models;
- Provide a methodology to architects to help them conduct a project-specific analysis (rather than using rules-of-thumb), given that they are key decision-makers and influencers;
- Showcase through visual results what can be done with existing products and mature technologies (including low-cost customisation techniques) through a palette of examples assessed in terms of qualitative (acceptability) and quantitative (energy, cost, …) aspects;
- Promote the idea that BIPV can become a *"raw material"* for architectural renewal projects, at the same level as traditional envelope materials (e.g. glass, ceramic, concrete, etc.), rather than a technical constraint for designers;
- Propose a design-driven and building-coherent BIPV sizing method based on the self-consumption (SC) and self-sufficiency (SS) ratios;
- Analyse the influence of different energy-use scenarios and the integration of battery storage systems;
- Develop a holistic assessment method following a parametric approach involving both existing methods and tools and an 'in-house' prototype tool;
- Allow comparing strategies to the 2'000-Watt Society targets through a life-cycle assessment (LCA) involving both the construction (renovation) and operational phases, highlighting the importance of choosing low-embodied energy materials during the design phase.

4. Identification of archetypal situations

This chapter is dedicated to the application of the first phase of the methodology (introduced in Chapter 2), which consists in the study of the residential building stock in the city of Neuchâtel, considered as a representative middle-size city of the Swiss Plateau. The final objective of this phase is to classify the building stock in different archetypal situations to subsequently find real case studies corresponding to these archetypes when moving on to Phase 2 (Chapter 5).

As seen in Chapter 3 (Section 3.1.1), in order to capture the essence of the built environment to be represented by archetypal building-scale cases, it is necessary to study the building stock starting at the urban level. First, statistical information and geo-referenced data have been collected, mainly from the census of the population and the registration of buildings. To guide the acquisition of this statistical data, a series of parameters that could provide relevant information in the context of BIPV implementation in renovation projects were previously defined (e.g. construction period, level of heritage protection, type of roof or the disposition within the urban context to highlight the availability of façades to produce photovoltaic electricity). Based on this prior definition of parameters, raw data containing the necessary information was obtained. A study (using GIS tools) was then made to define the possible values that each parameter should take, focusing on the residential building stock in Neuchâtel. For instance, for the type of roof parameter, the main values (or options) are flat or sloped roof. With just these two possible values, we can get an idea of the type of BIPV strategy that could be adopted. Once the possible values for each parameter were defined, a series of urban layouts and comparative charts have been generated allowing us to classify the buildings stock. From this classification were defined the different residential archetypal situations, each representing a major type of dwelling on the basis of which the selection of the real case studies is made in Chapter 5. Once renovation scenarios including BIPV strategies are proposed (Chapter 6), a multi-criteria assessment is conducted (Chapter 7) on each archetype and scenario.

The archetype-based approach allows us to design retrofit interventions with BIPV strategies by working at the building and constructive detail levels, producing representative / convincing examples based on real case studies. These detailed developed examples can serve as references to architects, to help them better address renovation processes of residential buildings integrating BIPV elements.

Due to the representativeness of the archetype-based case studies, results from their assessment (e.g. energy, LCA, …) could theoretically be scaled-up through simple multiplications by the number of dwellings (given by the statistical data) which fit the description of each archetype **[Swan et al. 2009]**. In that way, the current status and potential energy savings of a regional or national housing stock could be depicted. Although assessing the global energy performance and improvement potential of the whole building stock is not an objective of this thesis, our approach based on the archetype concept leaves the possibility of doing so.

4.1. Data collection

This section describes the data collected, analysed and processed to conduct the study of the residential building stock in the city of Neuchâtel, using a geographic information system (GIS) approach with geo-referenced data. The open source software used to manage, analyse and visualise these data is QGIS [**OSGeo 2018**].

In order to better select the required data, it was important to be clear with the objective of this urban scale study. As mentioned, the idea is to analyse the residential building stock of a representative city, in order to classify it in a set of archetypal situations. These archetypal situations should provide an overview of the different building typologies that architects will be confronted to in the near future, when a renovation process is proposed and the necessity to achieve the 2050 objectives becomes an obligation.

With this objective in mind, each archetypal situation is determined using a set of pre-defined parameters, related to the renovation potential and the opportunity to implement BIPV elements. These parameters notably concern the buildings solar exposure (relationship with the neighbouring buildings or urban context) and their available surfaces (façade and roofs), susceptible to receive active elements to produce on-site electricity that can be used by the building itself. While the parameters are listed below (on a priority basis), their corresponding values (or categories) are introduced in Section 4.4.

- **Construction period** (considered as a main parameter, representing all buildings that must be renovated in the near future, given their age).
- **Urban context** (as an indicator of the solar exposure potential or the relationship with the surrounding buildings).
- **Available surfaces to be active** (considering the size and morphology of the building; number of stories or height of the building (surfaces potential on façades) and type of roof (flat or sloped / curved); distinguishing different types of solar exposure, as well as different integration approaches of the active elements, which also has an influence on the type of photovoltaic product to be used).
- **Heritage protection / architectural quality** (to detect and avoid buildings with a high level of protection that prevents or hinders the implementation of certain renovation scenarios; when dealing with buildings with a higher level of uniqueness, this diminishes the potential for extrapolation of the results of the thesis as references for architects).
- **Type of ownership** (to take into consideration one of the main stakeholders in the renovation process, but also, because the type of owner, if chosen depending on the number of buildings they have, can facilitate on the one hand the task of disseminating the results of this research and on the other hand the task of selecting real buildings that match the definition of archetypal situations).

In addition to these parameters, and from a practical point of view, the selected buildings should not have been protagonists of previous major renovations, and we must have the possibility to obtain detailed information of each building (e.g. the possibility of visiting the building, obtaining plans / drawings, historical data about the maintenance or renovation interventions carried out in the past, as well as access to the energy bills to be able to study and model the current status of the building).

Considering all these criterion, two types of available statistical and GIS data are used to conduct this building stock study: geo-databases and vector maps (Table 4-1).

Geo-databases	
From the **Federal Register of buildings and Dwellings (RegBL) and national surveys** - Statistics of population and dwellings - Construction period - Building typology - Housing surface - Energy source - Heating system	3’187 buildings
From the **Land-owners register** - Name and general data - Property type	4’660 buildings
From the **Architectural heritage register** - Level of protection	3’247 buildings
Vector maps	
From the **Cadastre database** - Building footprints - Land plots - Streets	5’200 buildings
From the **Swisstopo** - GEOSTAT grid	

Table 4-1. Summary of data collection used in the urban study. Federal register **[OFS 2015c]**, National surveys **[OFS 2016a]**, Land-owner register **[Neuchâtel 2015a]**, Architectural heritage register **[Neuchâtel 2005]** and Cadastre database **[Neuchâtel 2015b]**.

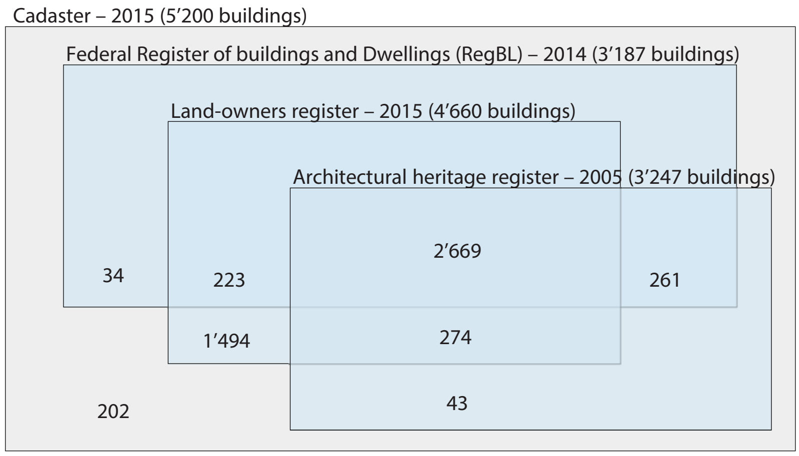


Figure 4-1. Intersection of the main geo-databased for the city of Neuchâtel showing the number of entries (buildings), including all buildings built until 2015.

However, some hypotheses could be made for the buildings which are not recorded in one or more databases (e.g. excluded from the RegBL, such as non-residential buildings, non-listed in the Architectural Heritage Register, as well as the most recent buildings or minor constructions). In this way, the robustness of the study should be guaranteed, provided that the decision-maker is made aware of such assumptions.

Since this research is focused on existing residential buildings that may be renovated (i.e. built before 2005), the fact that certain non-residential or more recent buildings are not accounted for in certain databases is not an issue.

The entire building stock, catalogued in the Neuchâtel Cadastre, holds 5’200 buildings with 5’901’101 m^2 of floor area. From those, out of all buildings built until 2015, 2’859 are residential buildings (Figure 4-2), which represent 3’097’125 m^2 of floor area. Regarding the constructions dating until 2005 (corresponding to buildings with a higher chance of being renovated), 90% are residential buildings (Figure 4-3), representing 3’033’070 m^2 of floor area.

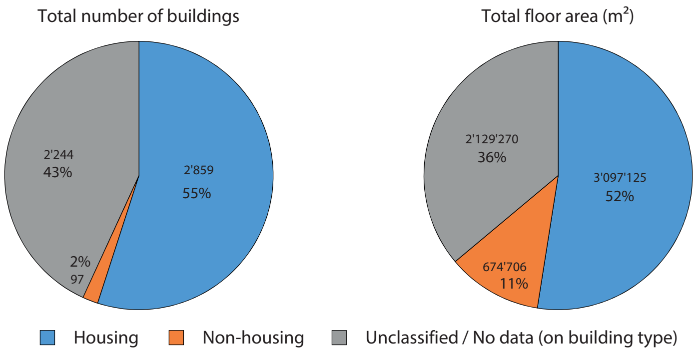


Figure 4-2. Classification of building types in Neuchâtel, for buildings built until 2015 **[OFS 2015c]**.

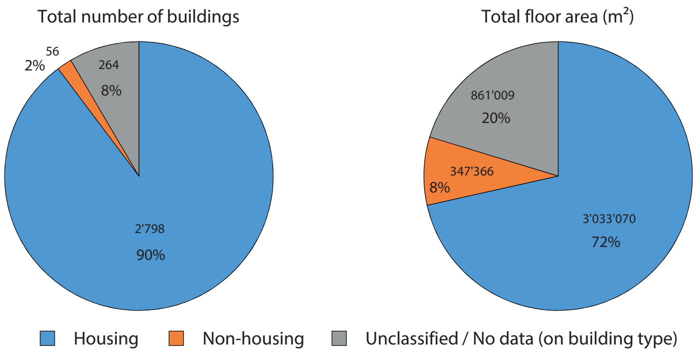


Figure 4-3. Classification of building types in Neuchâtel, for buildings built until 2005 **[OFS 2015c]**.

Using all the available data, the process of identification of the different archetypal situations can begin and is exposed in the following sections in order to:

- Show the correspondence between the evolution of the building stocks in Neuchâtel and the rest of Switzerland highlighting that Neuchâtel is a representative city.
- Show the importance of residential buildings with respect to all buildings in a city.
- Show the final selection of parameters (5 criteria) that will allow the study of the building stock.
- Show the analysis of the building stock based on a typological study including these 5 criteria in order to identify the combination that will define the different archetypal situations.
- Show a summary of the definition of the archetypes.

4.2. Neuchâtel as a representative city in Switzerland

This section shows the correspondence between the evolution of the building stock in Neuchâtel compared to other cities in Switzerland highlighting that Neuchâtel is representative of the typical middle-size city of the Swiss Plateau.

The Swiss Plateau is one of the three major geographical regions in Switzerland between the Jura Mountains and the Swiss Alps (Figure 4-4). It covers about 30% of the total Swiss territory. It encompasses many hilly areas, large lakes (Geneva, Neuchâtel, Zurich and Constance) and major rivers (the Aare, Sarine and Rhine). It has an average height varying from 400 to 700 m above mean sea level. It is the most important region of Switzerland with respect to economy and transportation, and is by far the most densely populated region.

Figure 4-4. Population in Switzerland by districts and the three main region in Switzerland, Jura, Plateau and Alps (data from 2015). Source: OFS - Statistique de la population et des ménages (STATPOP) **[OFS 2015d]**.

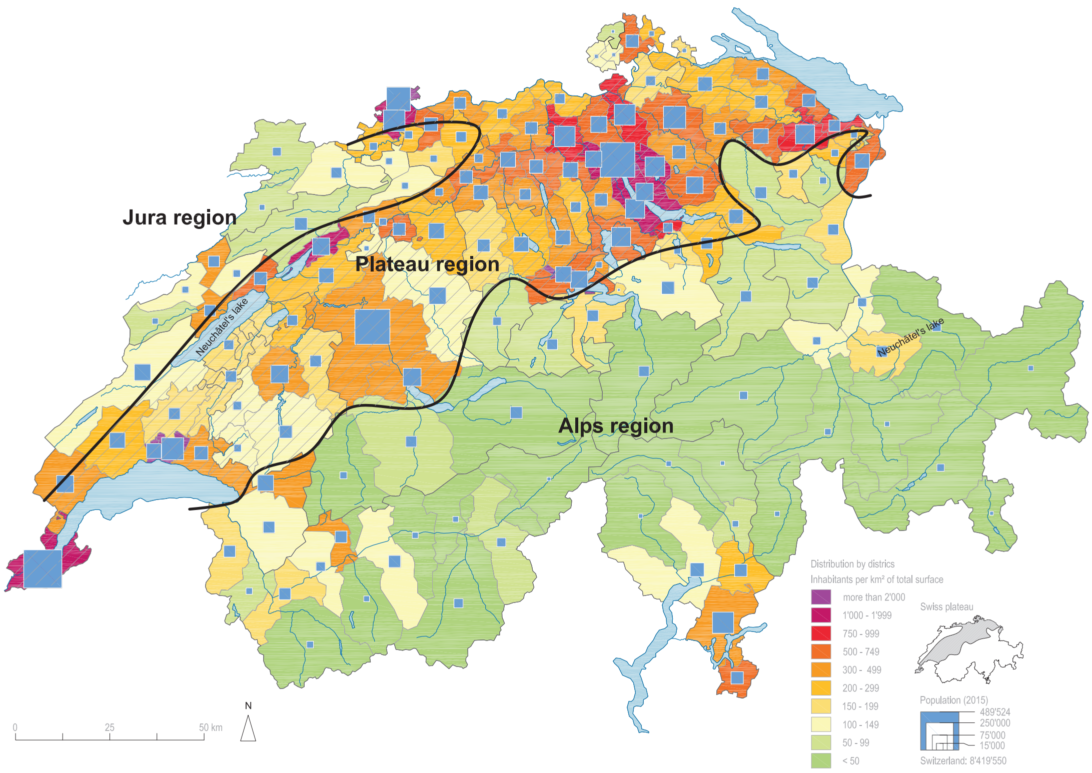


Figure 4-6 highlights the similar trends of the construction development between Neuchâtel and Switzerland according to the different construction periods and for four types of residential buildings defined by the Federal Statistical Office **[OFS 2015c]**: (1) single-family houses, (2) multifamily houses, (3) residential buildings with annex uses, and (4) partially residential buildings.

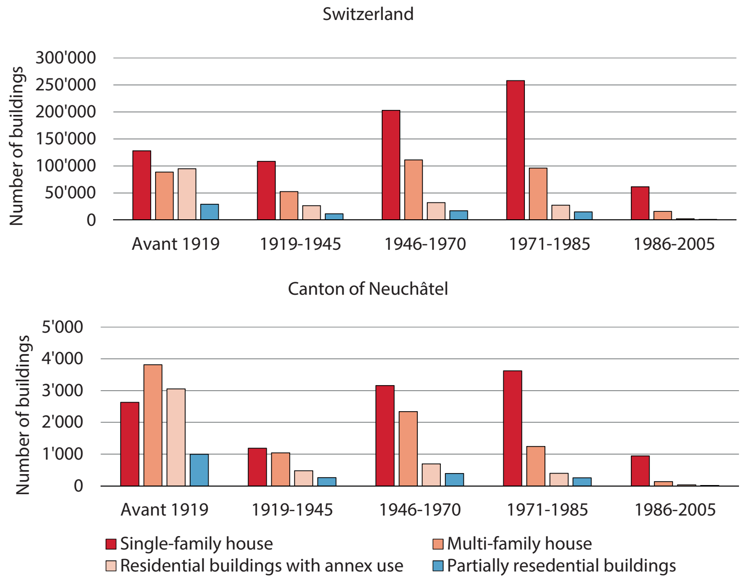


Figure 4-6. Total of buildings built in Switzerland (top) compared to the Canton of Neuchâtel (bottom) for different construction periods and type of residential building types **[OFS 2016b]**.

Moreover, considering the following additional aspects, the city of Neuchâtel stands out as particularly relevant for this thesis: 1) strong interest of Neuchâtel for energy efficiency and renewable energy issues (Energy City Label, European Energy Award GOLD, member of the European HOLISTIC Consortium), 2) availability of data necessary for the realisation of this research, such as the statistical geo-database **[OFS 2015c]** and cadastre **[Neuchâtel 2015b]**, which have been completed in previous studies, and 3) presence of the Swiss Centre for Electronics and Microtechnology (CSEM) **[CSEM 2018]** involved in photovoltaic research.

Figure 4-7 shows the different developments of the city according to the construction period. Most buildings were built before 1985 and have a low-level of energy performance, partially due to the lack of energy regulation (for more details see Figure 4-10 and Figure 5-3 in Section 5.2). This situation remains similar nowadays because of the low renovation rate of about 1% **[CCEM 2012a; Jad 2014; Passer et al. 2018]**.

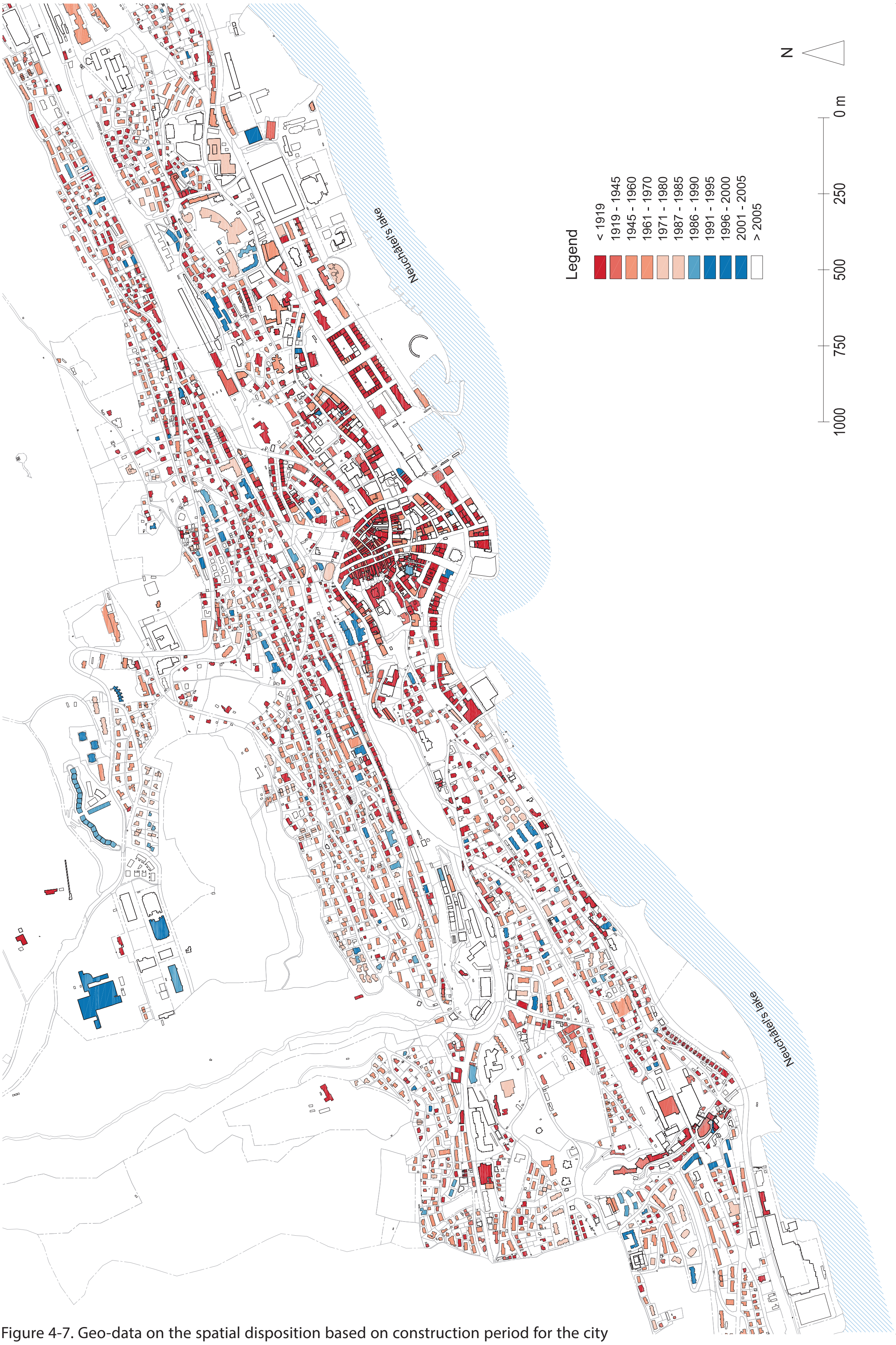


Figure 4-7. Geo-data on the spatial disposition based on construction period for the city of Neuchâtel, data from 2015.

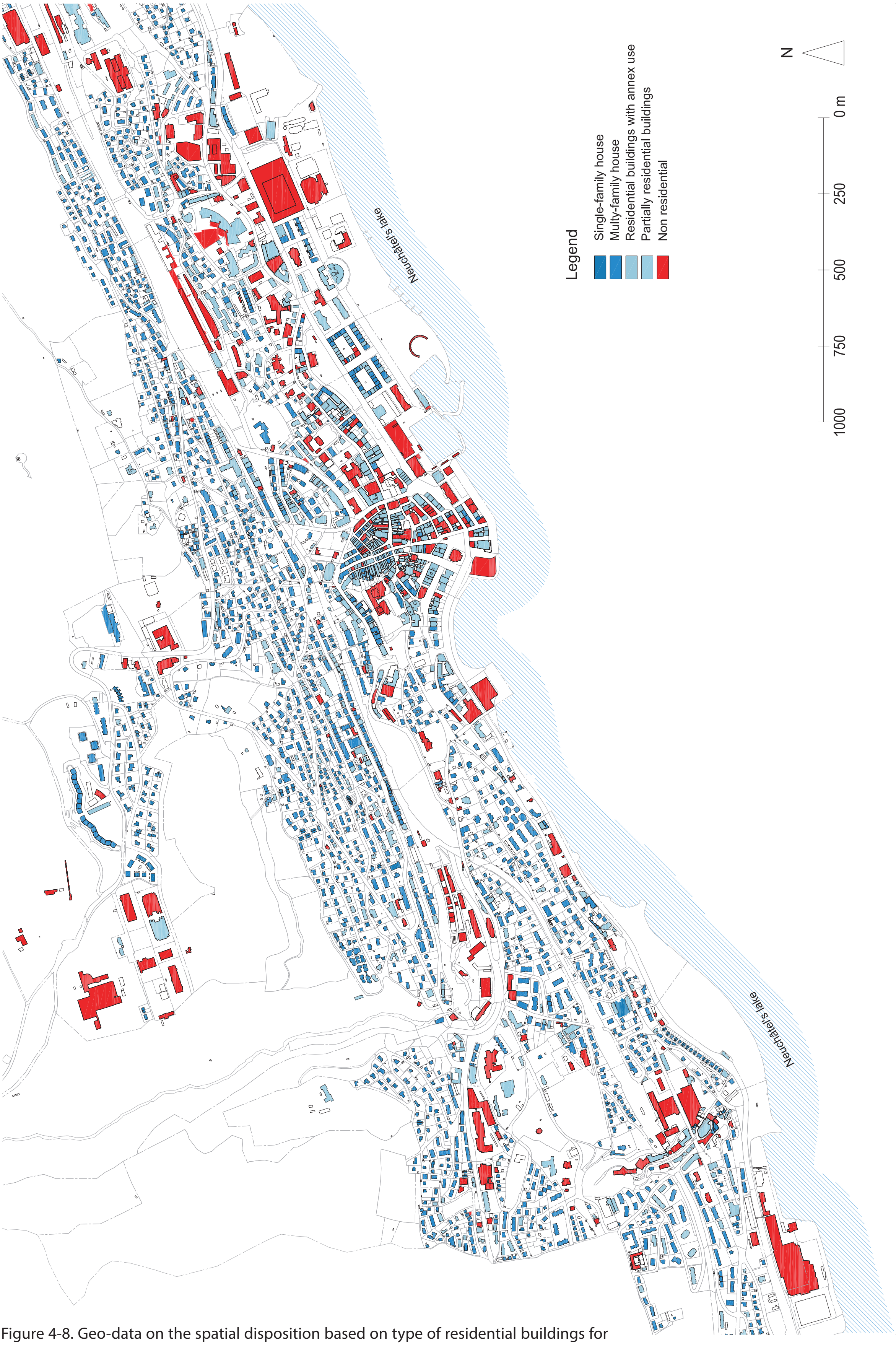


Figure 4-8. Geo-data on the spatial disposition based on type of residential buildings for the city of Neuchâtel, data from 2015.

Buildings situated in the historical centre were built before 1919 and are, for the most part, protected by the Architectural Heritage Service of Neuchâtel **[Neuchâtel 2005]**. Since the implementation of PV on historical buildings presents some particular barriers due to the high level of protection of such buildings **[Kandt et al. 2011]**, and that PV solutions for historical buildings (often peculiar) remain too specific to be reproducible on other projects, we here focus on common residential buildings that have a heritage level of protection that allows renovating their thermal envelope (as seen in Section 4.4).

Figure 4-8 shows the repartition of the building typologies throughout the city. We clearly see that most buildings have a residential use (in blue), and the majority are single-family houses and multifamily buildings with and without annex uses (e.g. commercial space on the ground floor). Likewise, the predominant typology in the centre and in the most commercial streets are of type 3 (residential buildings with annex uses) and 4 (partially residential buildings). The next section further justifies our focus on residential buildings.

4.3. Focus on residential buildings

According to the literature review presented in Chapter 3 (Sections 3.1 and 3.2), there are recent publications about BIPV integration in buildings, specifically in new and non-residential buildings [**Yang et al. 2016**]. However, there is a lack of studies convening renovation of residential buildings with BIPV through an interdisciplinary research approach.

Furthermore, residential buildings do not appear to have been specifically addressed in research up to date. In most of the literature reviewed, case studies in renovation projects belong to the category of the most singular buildings – which tend to be isolated from the urban context that we want to study in this thesis – such as historical buildings (e.g. Herz-Jesu church in Plauen, Germany), public buildings (e.g. Public Utilities Building in Aachen, Germany) or the tertiary building sector **[Eiffert et al. 2000; Gaiddon et al. 2009; Jelle et al. 2012b, 2012a; Cerón et al. 2013]**.

As can be seen in Figure 4-9 and Figure 4-10, the majority of buildings use fossil fuels (oil and gas) through boiler systems to respond to their heating and domestic hot water (DHW) demand. This situation means there is a great improvement potential in terms of greenhouse gas (GHG) emissions and primary energy savings. Conversely, if the 2050 targets **[SIA 2017a, 2018]** are to be achieved, it is essential that the residential building stock be renewed and this need can be viewed as a great opportunity for the integration of photovoltaic energy, rendering active the building skin.

We thus focus on residential buildings due to 1) the lack of exiting studies, 2) the importance of this kind of buildings in cities, 3) the amount of energy used by these buildings, and 4) the fact that they were built before 1985 and thus represent a significant renovation potential for the following years.

In the following sections, the definition of the different archetypal situations is exposed.

4.4. Selection criteria parameters and GIS data treatment

In order to identify the different categories for the pre-selected parameters that guided the data acquisition process (Section 4.1), a data analysis was conducted using the QGIS tool **[OSGeo 2018]**. The results provide us with the selection criteria for choosing real case studies (Chapter 5).

As the main parameter (A), we have considered the period of construction **[CCEM 2012a]** because it is a strong indicator of the type of constructive building system and it is one of the indicators used to define the level of protection according to the Communal master plan art. 115 **[RA 2007]**.

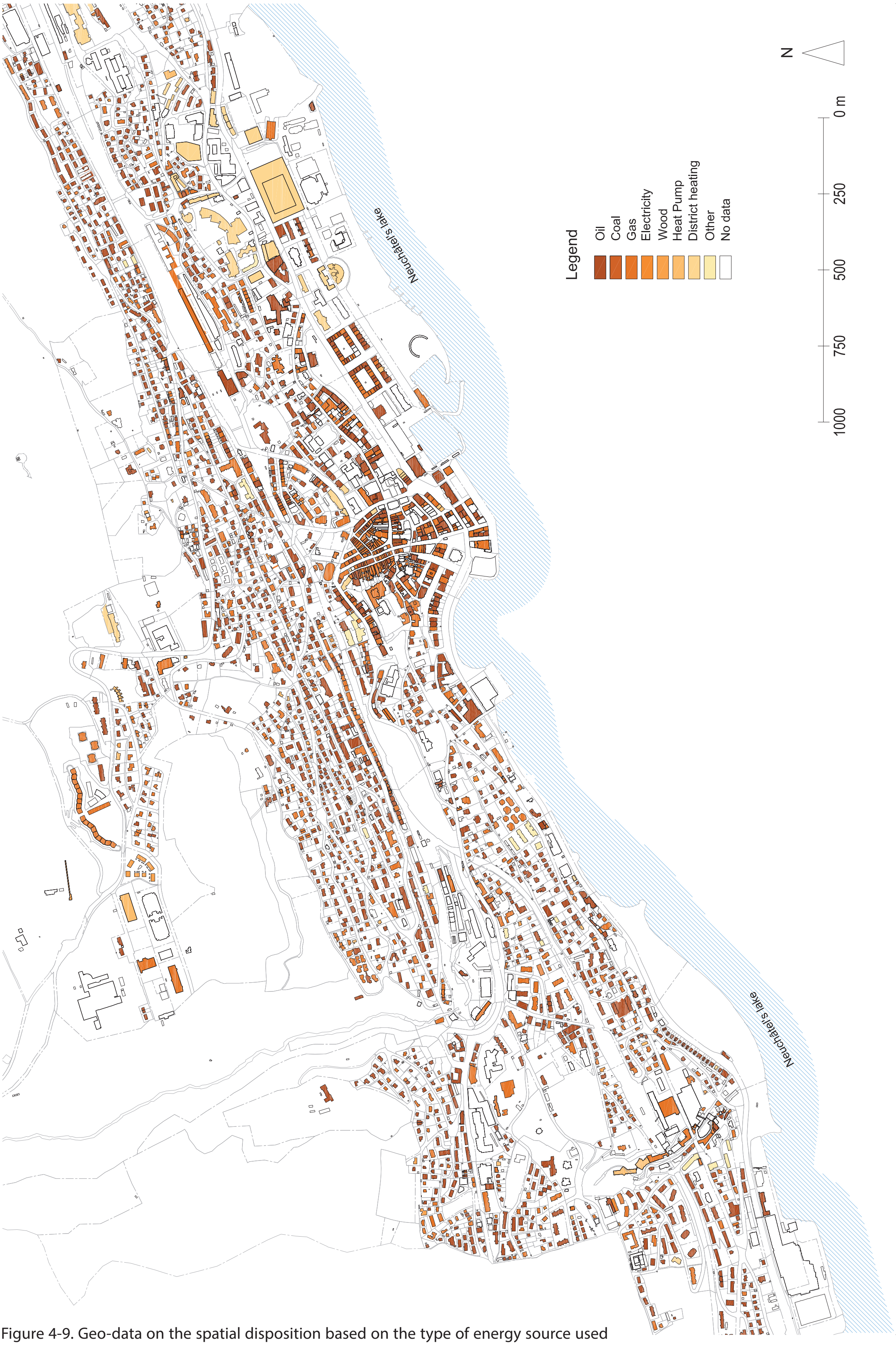


Figure 4-9. Geo-data on the spatial disposition based on the type of energy source used by buildings to cover their heating demand, data from 2015.

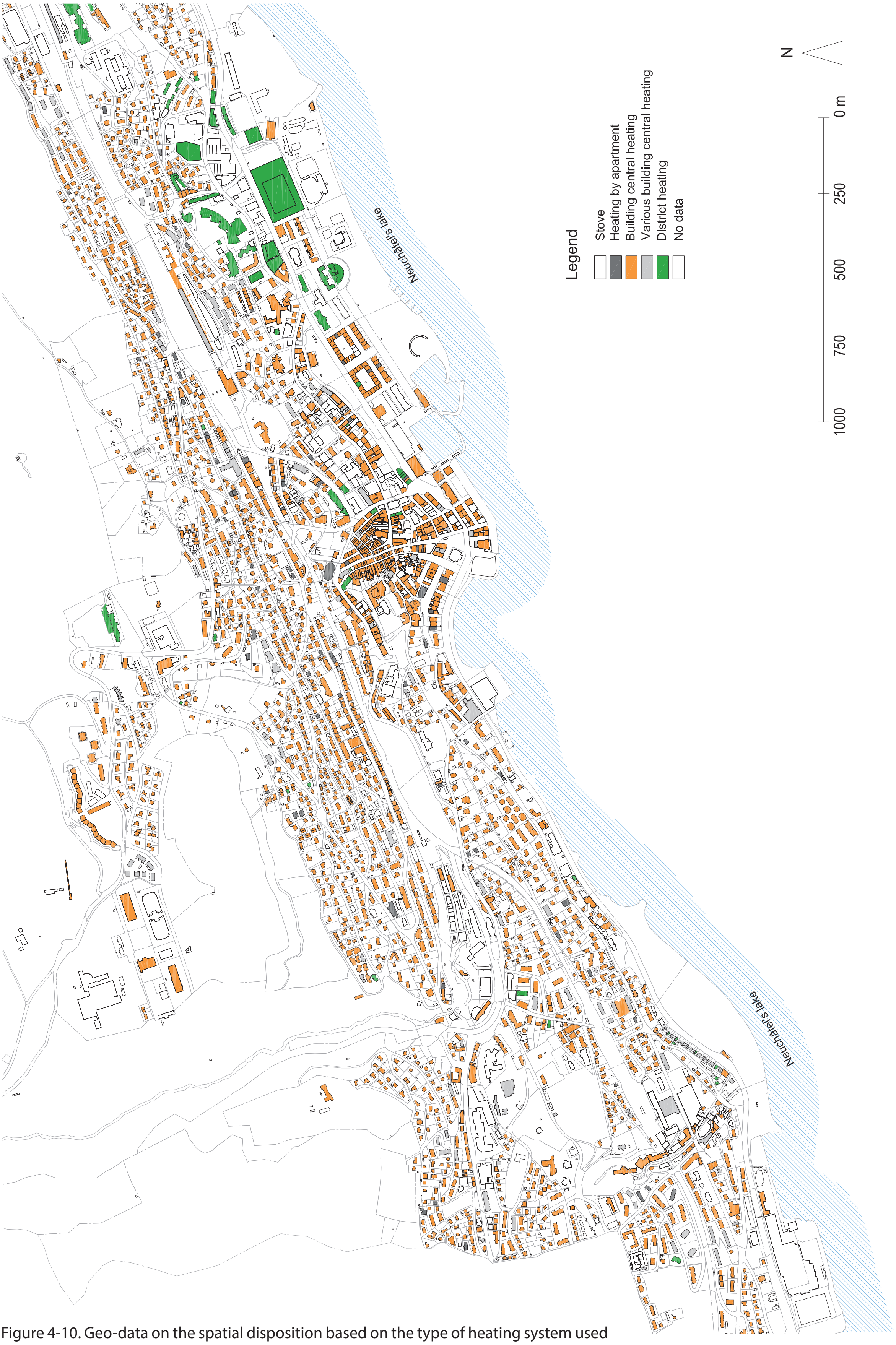


Figure 4-10. Geo-data on the spatial disposition based on the type of heating system used by buildings, data from 2015.

With the purpose of identifying the most representative construction periods, we have crossed the Register of Buildings and Dwellings (RegBL) data **[OFS 2015c]** according to the year of construction with the different historical periods of architecture and its political / economic context. To illustrate this, Figure 4-11 presents the number of buildings built until 2005, highlighting the different historical milestones in relation to the type of buildings and the energy context.

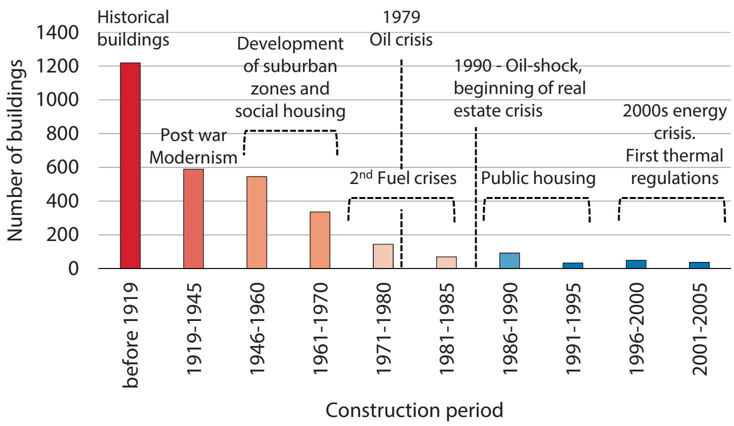


Figure 4-11. Number of buildings by construction period in Neuchâtel, and the main historical milestones.

From these construction periods, some aggregations were done to better balance the number of buildings in each bin, while taking into consideration similarities in terms of constructive features between the different periods, as well as the socio-economical context. As such, the 1946-1960 and 1961-1970 were merged, so were the 1971-80 and 1981-85 periods, leading to the fifth and final period covering the years 1986-2005. This simplification should however not affect the robustness of the methodology, which can be applied with a higher level of detail in terms of number of construction periods considered if needed.

An aggregation was also done for the roof type parameter (C). The diversity of roofs shapes present in the data and studied with QGIS has allowed to identify up to eight different roof types (Gabled, Hipped, Flat, Shed, Pyramidal, Mansard flat, Mansard hipped and Curved), which correspond to the list proposed in a study of the city of Geneva (Switzerland) [**Mohajeri et al. 2018**]. However, these were aggregated down to two types, flat roof or sloped roof, because these two types represent well the two kinds of strategies of solar energy integration on roofs. In general, flat roofs allow for less integrated PV elements (standard panels, prioritising low-cost installation based on a BAPV concept) as the visual impact is less significant than sloped roofs. For the latter, no matter the type (e.g. gable), better adapted products are needed to increase acceptability in a built environment (customised panels in terms of size or visual aspect, prioritising the BIPV concept).

The Architectural Census of the Canton of Neuchâtel (RACN) **[Neuchâtel 2005]** evaluates each building located in urbanised areas through the cantonal commission of cultural property and the office for the protection of monuments and sites. Each building is classified from high (grade 0) to low (grade 9) level of heritage protection according to its architectural and historical qualities.

These grades are used to divide buildings into the following three categories that we also use in this thesis:

Category I (interesting buildings):

- Grade 0 (noteworthy): qualities are recognised unanimously.
- Grade 1 (multiple interests): less prestigious, but presenting a set of undeniable qualities.
- Grade 2 (obvious interest): presenting at least one undeniable quality.
- Grade 3 (possible interest): generally less elaborated but presenting qualities that invite, following a summary analysis, further historical or archaeological research.

Category II (typical or picturesque buildings):

- Grade 4 (typical): has qualities of a current construction, without presenting the interest of an example, and integrating well with the site.
- Grade 5 (picturesque): characterises an altered volume or having an interest difficult to evaluate, considered picturesque because the interest cannot be specified otherwise.
- Grade 6 (neutral or banal): neither remarkable qualities nor troublesome defects.

Category III (disturbing buildings):

- Grade 7 (uninteresting): with many defects, but not very prominent.
- Grade 8 (disturbing): many defects, unsuited to the site.
- Grade 9 (evidently disturbing): alters the site, disappearance desirable.

The classification with nine grades allows a higher level of finesse when it comes to knowing the restrictions at the time of proposing a renovation project, but for our research we consider that this level of detail is not necessary and therefore we remain at the level of the three main categories (I, II, and III) for the level of heritage protection (parameter E).

Finally, apart from taking the construction period as a main parameter to identify the different archetypal situations, five other selection parameters are added, based on the availability of the statistical data (Section 4.1) and the relevance in terms of BIPV integration in renewal processes.

The six selection parameters are described below and shown along with their respective possible values in Figure 4-12.

A. - **Construction period**: related to the definition of the constructive system and the energy performance in the current status of the building, this parameter has five values, covering the main construction periods.

B. - **Urban context**: related to the proximity to the other buildings and the available surfaces on the façade, this parameter has two options.

C. - **Roof potential**: allows to distinguish the two main types of existing roofs, implying different approaches in terms of photovoltaic integration.

D. - **Façade potential**: defined to classify buildings according to their height. This is a parameter that indirectly indicates the amount of façade available as a function of the number of apartments or housing units, therefore the concentration of energy demand, which influences the dimensioning of the photovoltaic installation.

E. - **Architectural quality / level of protection**: presents the three categories defined by the Architectural Heritage Service of Neuchâtel **[Neuchâtel 2005]**. Each category presents different levels of protections and consequently poses a different level of difficulty when intervening on the thermal envelope of the building (especially from an aesthetic / visual point of view). Therefore, we focus on buildings classified under category II and III, which do not have such a high level of heritage protection and therefore have a higher probability of being renewed.

F. - **Type of owner**: three main types of ownership are identified. As shown in the following sections, the strategy is to focus on large owners to facilitate finding real buildings within the stock of buildings owned (e.g. financial entities, the municipality or pension funds). Therefore, this is a parameter that is used informatively, because it offers a vision of how the national real estate market works, but it is not a key parameter in the definition of the archetypes.

A - Construction period

before 1919	1919-1945	1946-1970	1971-1985	1986-2005

B - Urban context

B1: Isolated / detached building	**B2**: Adjacent building

C - Potential of surfaces (Roof)

Roof type

C1: Flat	**C2**: Sloped / Curved

D - Potential of surfaces (Facades)

Building height

D1: 1-4 floors (~5-14 m)	**D2**: 5-7 floors (~17-22 m)	**D3**: >7 floors (~>22 m)

E - Architectural quality / Level of protection

E1: I – Interesting / protected	**E2**: II - Typical / common	**E3**: III - Unattractive / disturbing

F - Type of owner

F1: Co-ownership (PPE)	**F2**: Small owner (<3 proprieties)	**F3**: Large owner (≥3 proprieties)

Figure 4-12. Set of parameters and their corresponding possible values, used to identify the archetypal situations.

Based on these parameters (Figure 4-12) and the GIS data, graphical representations were produced at the urban scale – on the spatial (from Figure 4-13 to Figure 4-18) and temporal disposition (from Figure 4-19 to Figure 4-24, in Section 4.5) – to identify which are the combinations of these parameters that better define the different archetypal situations, always on the basis of comparing the main construction periods.

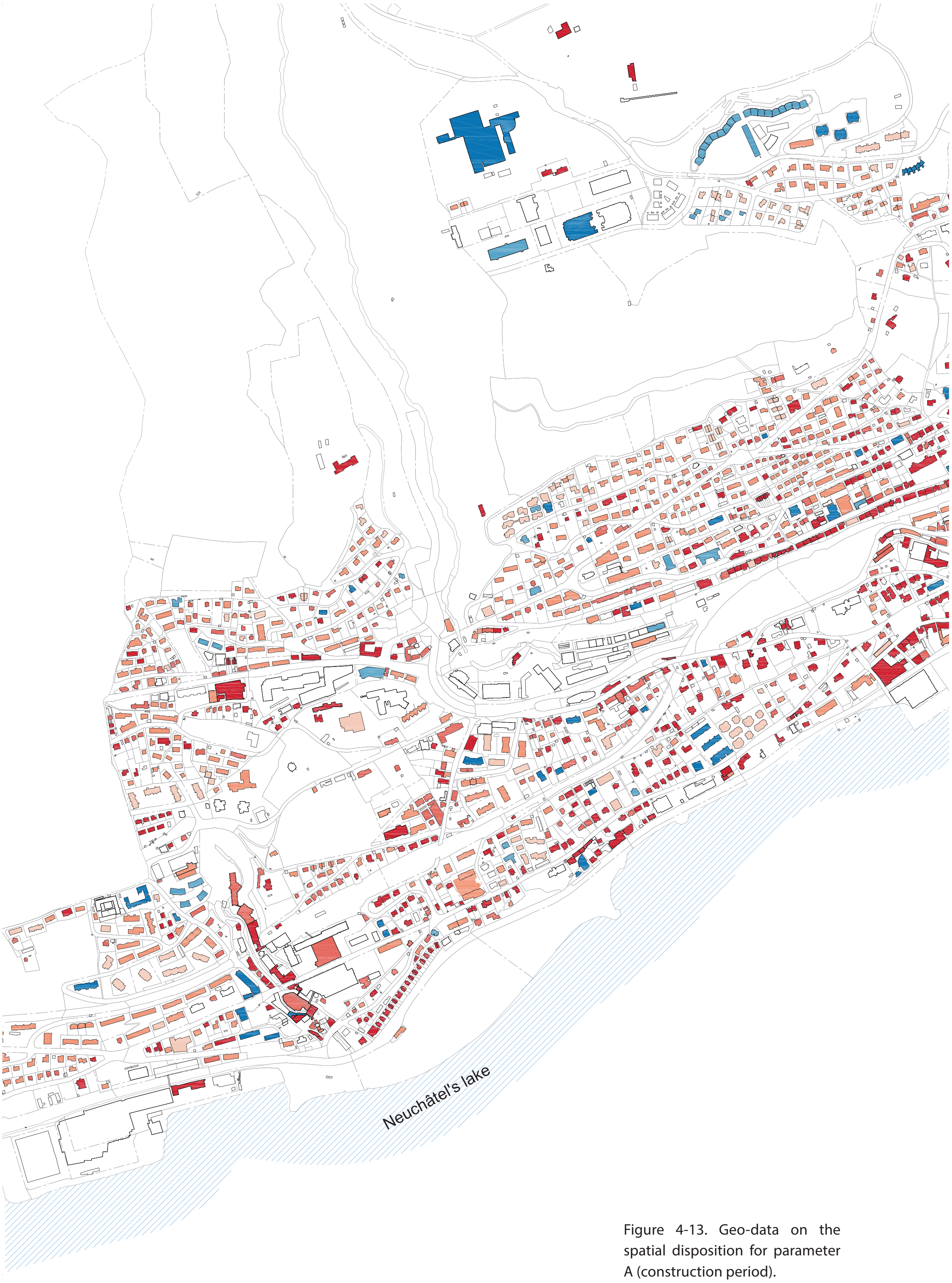


Figure 4-13. Geo-data on the spatial disposition for parameter A (construction period).

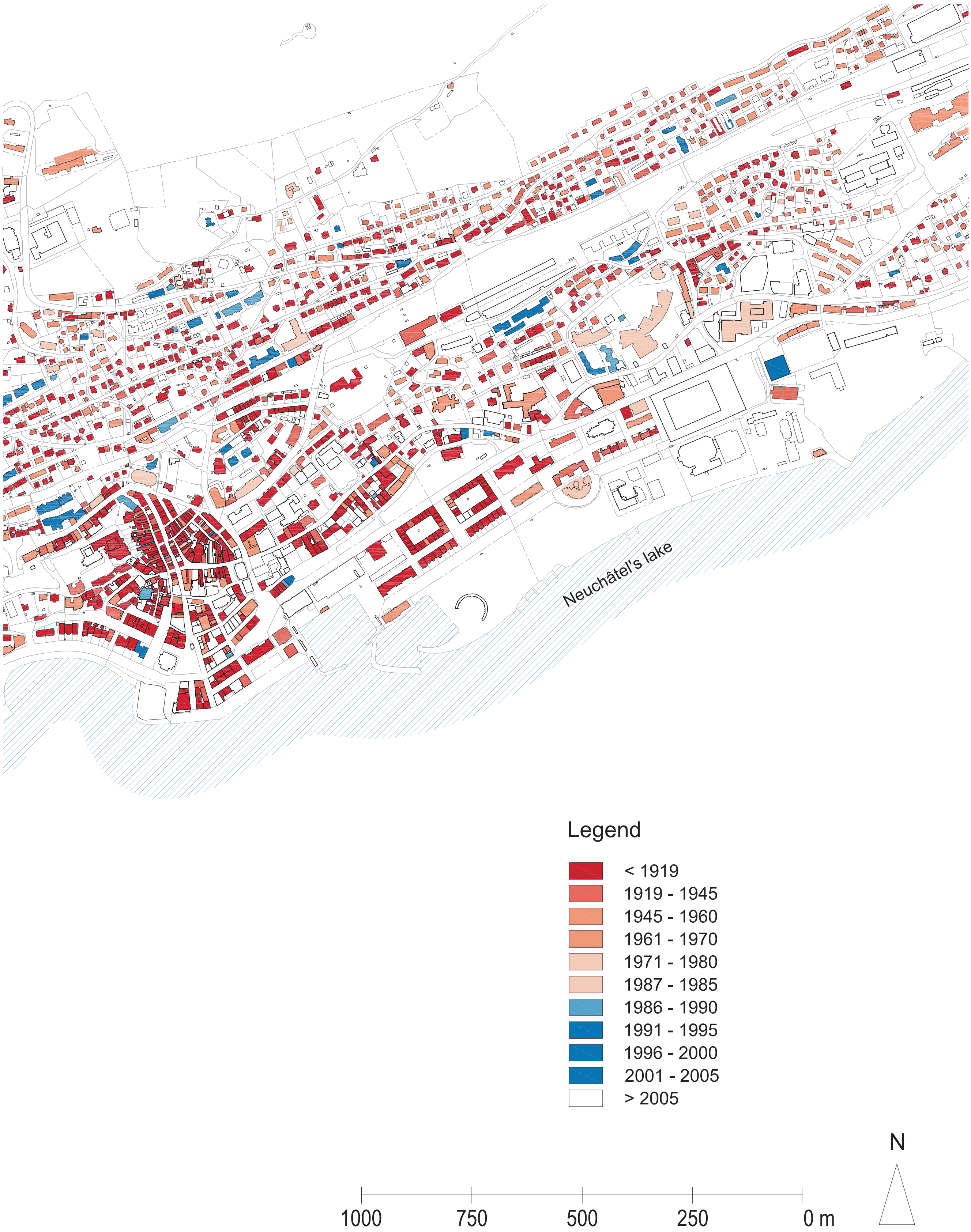

Neuchâtel's lake
Legend
< 1919
1919 - 1945
1945 - 1960
1961 - 1970
1971 - 1980
1987 - 1985
1986 - 1990
1991 - 1995
1996 - 2000
2001 - 2005
> 2005
N
1000
750
500
250
0 m

Figure 4-14. Geo-data on the spatial disposition for parameter B (urban context).


Neuchâtel's lake
Legend
Adjacent
Isolated
Non residential
1000
750
500
250
0 m
N

Figure 4-15. Geo-data on the spatial disposition for parameter C (roof potential).


Neuchâtel's lake
Legend
Sloped / curved roof
Flat roof
Non residential
1000
750
500
250
0 m
N

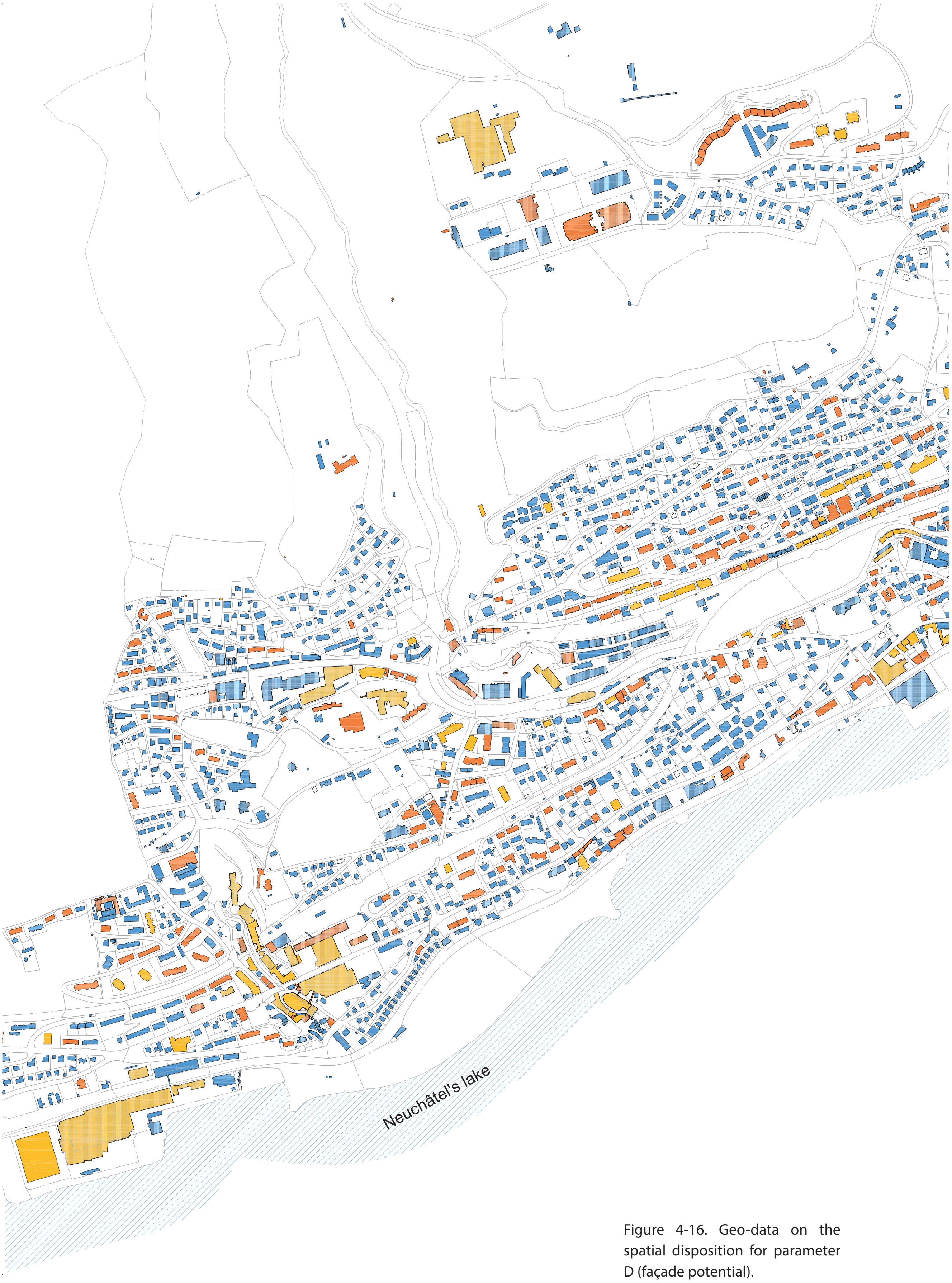


Figure 4-16. Geo-data on the spatial disposition for parameter D (façade potential).

Neuchâtel's lake
Legend
1 - 4 stories
5 - 7 stories
> 7 stories
Non residential
1000
750
500
250
0 m
N

Figure 4-17. Geo-data on the spatial disposition for parameter E (architectural quality / level of protection).


Neuchâtel's lake
Legend
Category - I Interesting
Category - II Typical
Category - III Disturbing
Unclassified
Non residential
1000
750
500
250
0 m
N

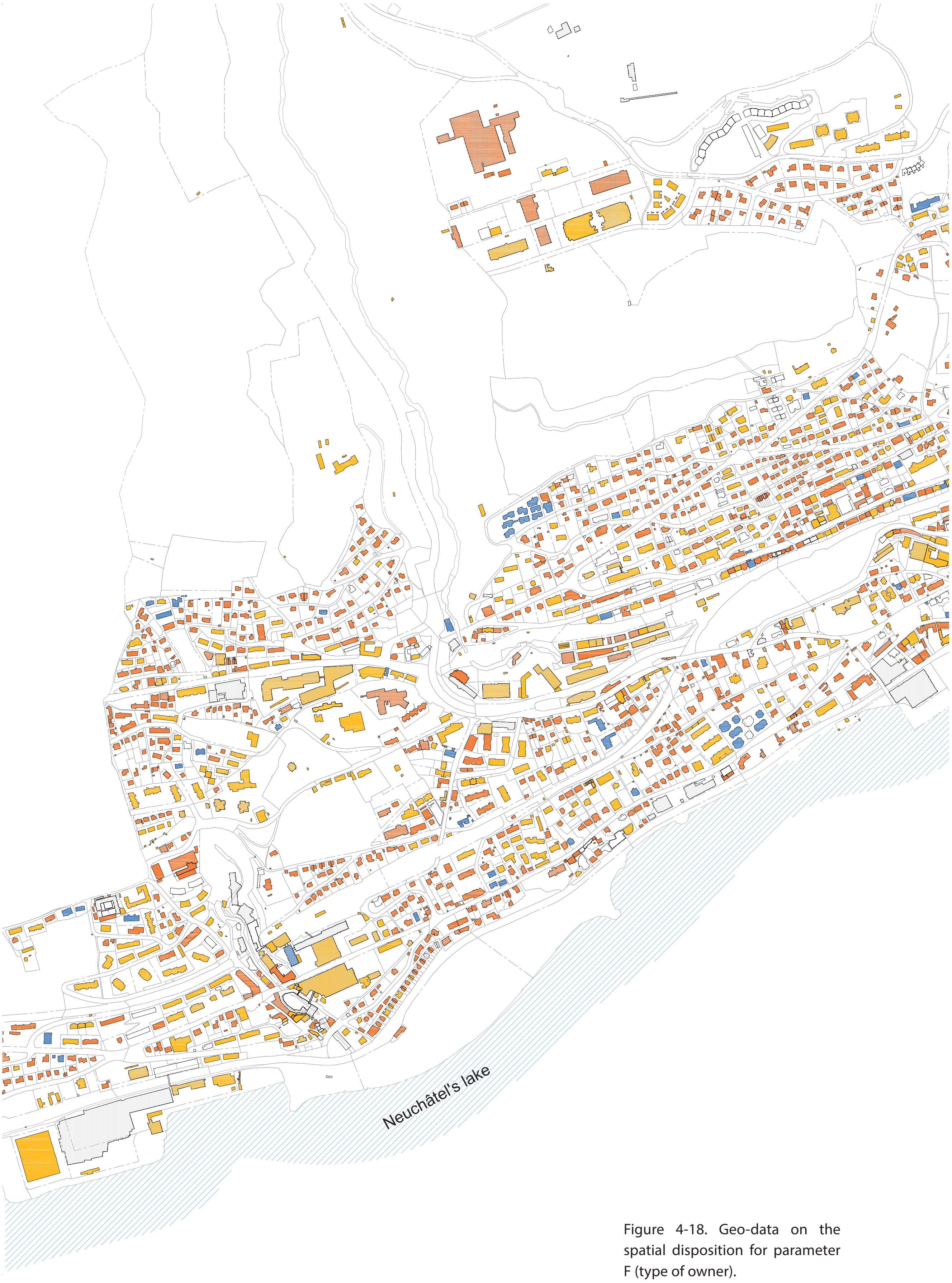
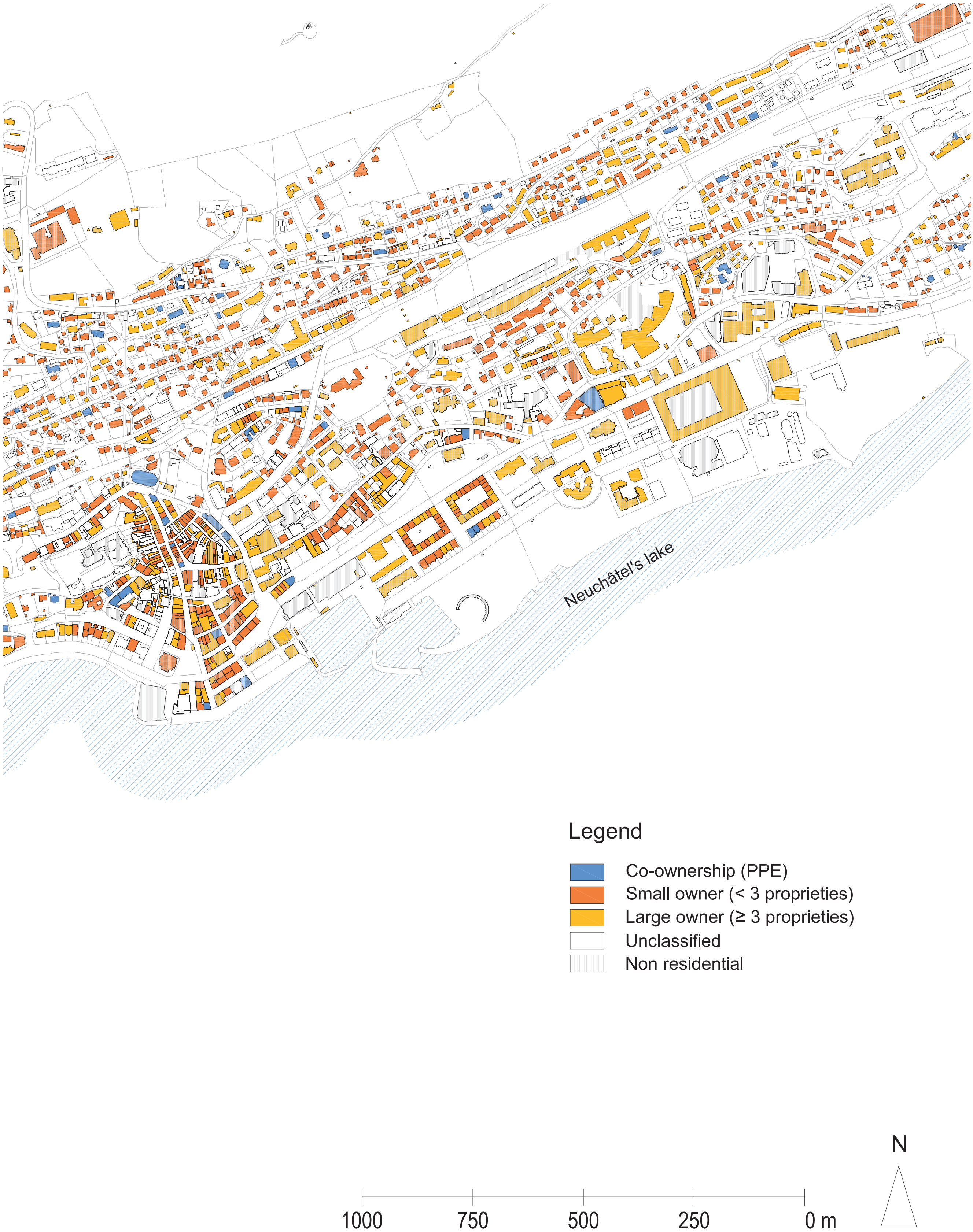


Figure 4-18. Geo-data on the spatial disposition for parameter F (type of owner).


Neuchâtel's lake
Legend
Co-ownership (PPE)
Small owner (< 3 proprieties)
Large owner (≥ 3 proprieties)
Unclassified
Non residential
1000
750
500
250
0 m
N

The different layouts with the spatial representation of all collected data give an overview of the type of building stock of the city of Neuchâtel, which, as seen earlier, follows a very similar pattern of development as any Swiss city. A large portion of the buildings were built before 1985 and have a detached configuration with the exception of the historical city centre. A large proportion of the buildings have an inclined roof with the exception of larger buildings or large residential complexes built around the 60s. The highest buildings are located in the centre and on the periphery of the city (with buildings between 5-7 stories or more than 7). In the rest of the city, built on old vineyards fields, buildings have between 1 and 5 stories.

In terms of protection, the most restrictive category (category I) is concentrated in the centre of the city, as well as the different urban developments in front of the lake. Aside from specific exceptions, the rest of the city belongs to the categories II and III, the latter usually formed by the most recent buildings, built after 1985.

The representation of the parameter about the type of owner highlights the Swiss system in which most of the apartments are rented and the buildings belong to large owners (e.g. financial entities, the municipality or pension funds). Only occasional exceptions are in a co-ownership regime, where each apartment within the same building belongs to a different owner, either individual private owners or organised in housing cooperatives.

In the next section, we look at the decomposed data for each parameter in order to define five archetypes of the most representative buildings.

4.5. Building stock analysis and residential archetypes definition

This section presents the analysis of the building stock through the data according to the different selection criteria defined in Section 4.4, in terms of number of buildings and corresponding floor area. The different residential archetypes are defined by combining the parameters in order to best represent each archetypal situation, using the construction period as a basis parameter.

Figure 4-19 shows the number of residential buildings built until 2005 and their equivalent floor area, totalling 3'017 buildings with 3'650'921 m^2 of floor area. As mentioned earlier, from the 3'079 buildings built until 2015, we exclude those built between 2006-2015 as they are not yet ready to be renewed.

The subsequent Figure 4-20 to Figure 4-24 present the results of crossing the different selection criteria (B-F) with the construction period (parameter A). It is important to highlight that depending on the period of construction, a unique combination can be difficult to find, because, for a specific parameter two or more options may have a similar weight (both in terms of number of buildings or in floor area). Or, the dominant option may be different depending on if the number of buildings is taken as the indicator or the floor area.

For instance, we see from Figure 4-20 that buildings built prior to 1919 are almost equally either isolated (585 buildings) or adjacent (475 buildings). There is no strong dominance of one case over the other for this parameter B and construction period. Moreover, when compared in terms of floor area, we observe the opposite (slightly larger weight for the adjacent category).

For the construction period of 1946-1970, we observe in Figure 4-21 that, by number of buildings, the type of roof that dominates is the sloped one, but according to the floor area, the flat roof is the most representative. This is due to the fact that during the period of 1946-1970, many small buildings (small owners) with a sloped roof have been built, but at the same time, it is the period when large residential buildings (large owners) with a flat roof were also built (Figure 4-24). These heavily contribute in terms of floor area but less so in terms of number of buildings.

Another example is the parameter F (type of owner, Figure 4-24), for which the data is almost equally split among the three options for buildings from 1971-1985 and 1986-2005. Such results are likely partly caused by the number of construction periods considered and the aggregation made.

The way through which these situations were handled when defining the archetypes is explained below.

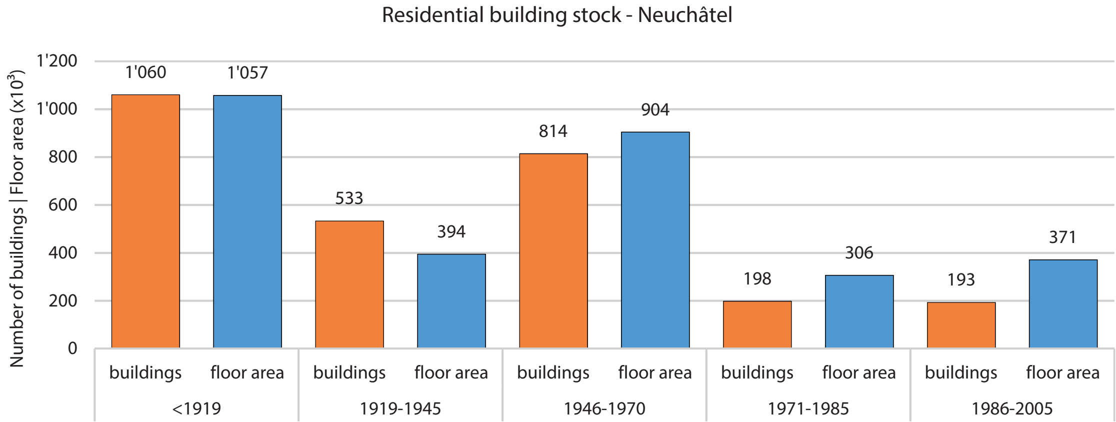


Figure 4-19. Parameter A, number of residential buildings and floor area for the five construction periods.

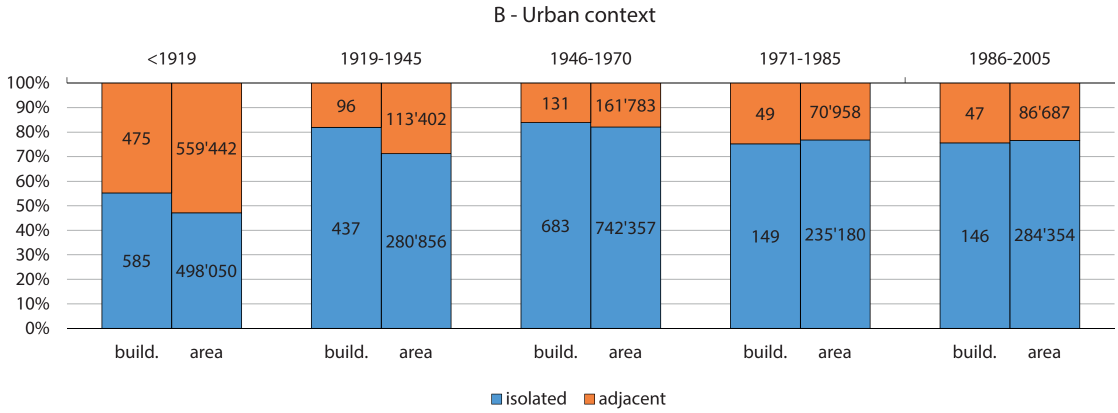


Figure 4-20. Parameter B, related to the urban context, expressed in number of residential buildings and floor area for the five construction periods.

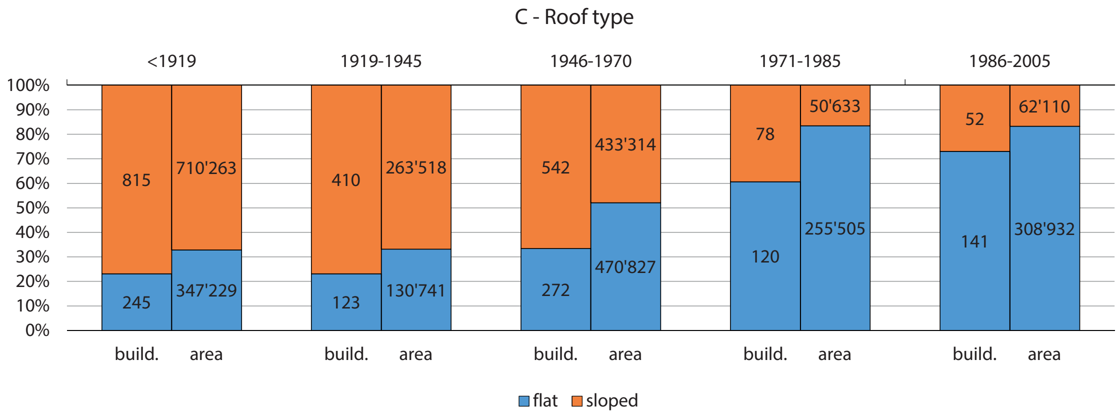


Figure 4-21. Parameter C, roof type, expressed in number of residential buildings and floor area for the five construction periods.

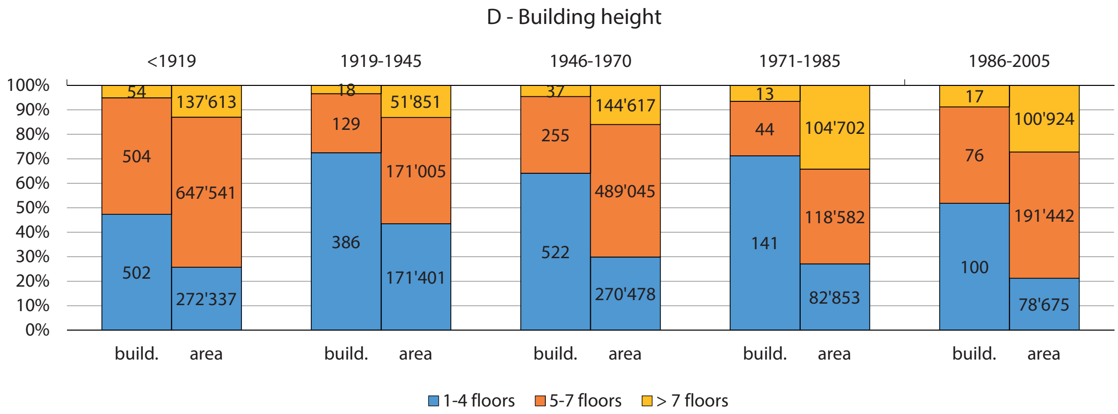


Figure 4-22. Parameter D, building height, expressed in number of residential buildings and floor area for the five construction periods.

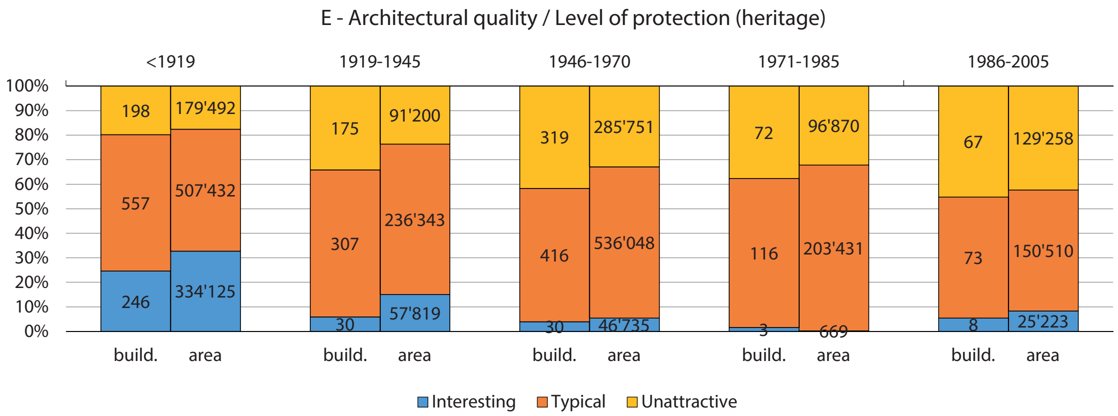


Figure 4-23. Parameter E, level of protection (heritage), expressed in number of residential buildings and floor area for the five construction periods.

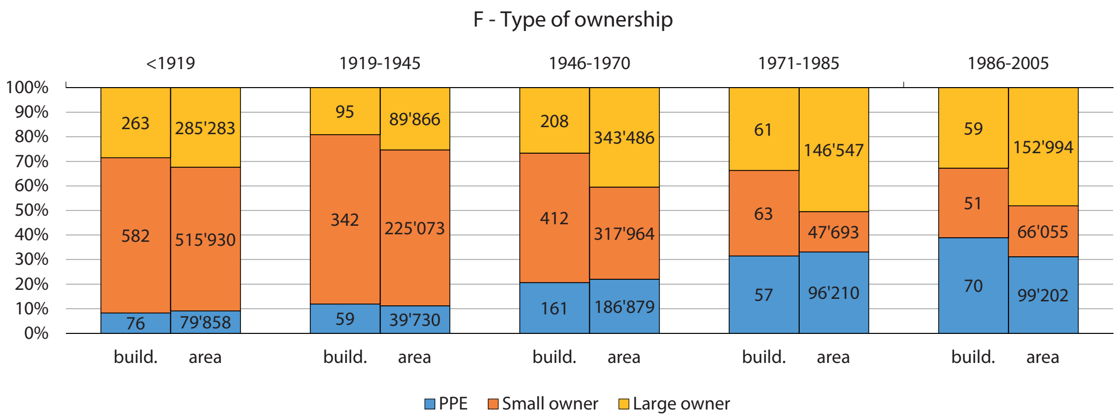


Figure 4-24. Parameter F, type of owner, expressed in number of residential buildings and floor area for the five construction periods.

Figure 4-25 to Figure 4-29 shows the number of buildings corresponding to the crossing of the different parameters in order to define the most representative combination for each construction period. The data represented in these sunburst diagrams include residential buildings classified as common and unattractive, excluding the most protected category (interesting or singular buildings). Data include all types of owners (PPE, small and large).

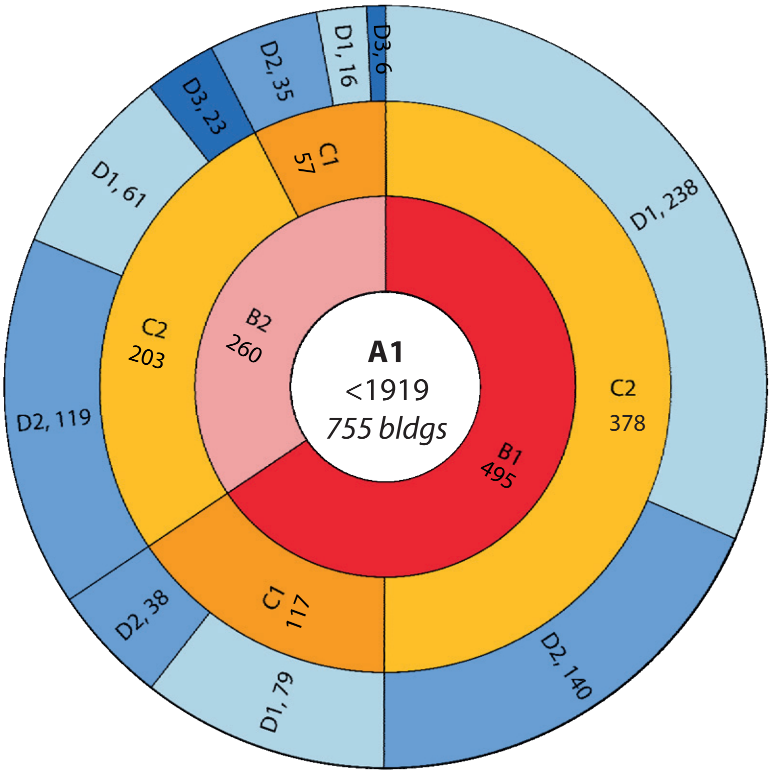


Figure 4-25. Sunburst diagram for construction period A1 (< 1919). Expressing the number of residential buildings for each intersection.

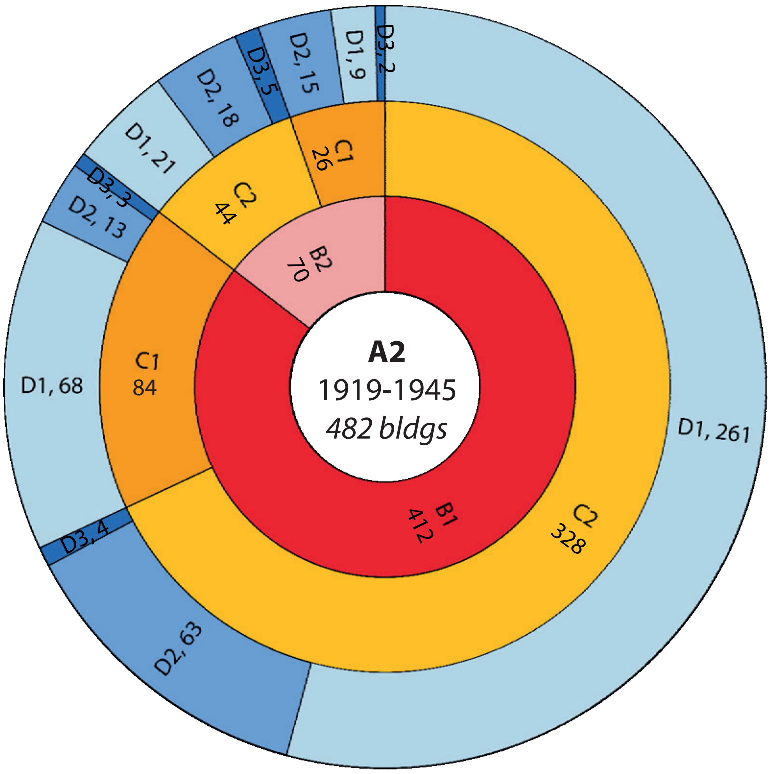


Figure 4-26. Sunburst diagram for construction period A2 (1919-1945). Expressing the number of residential buildings for each intersection.

Nomenclature: B – Urban context (B1 – Isolated building, B2 – Adjacent building); C – Roof type (C1 – Flat roof, C2 – Sloped roof); D – Building height (D1 – 1-4 floors, D2 – 5-7 floors, D3 - > 7 floors).

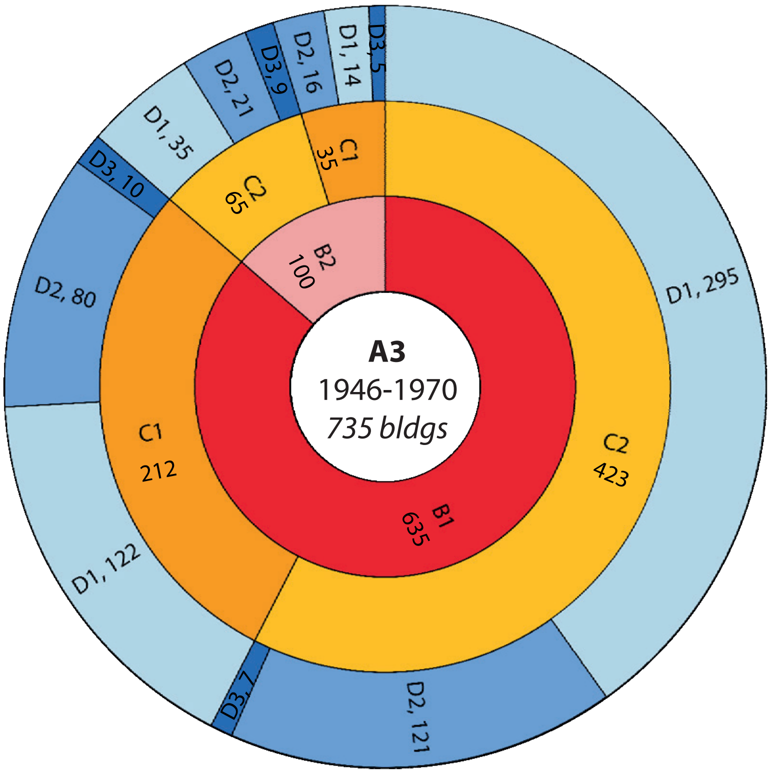


Figure 4-27. Sunburst diagram for construction period A3 (1946-1970).

Expressing the number of residential buildings for each intersection.

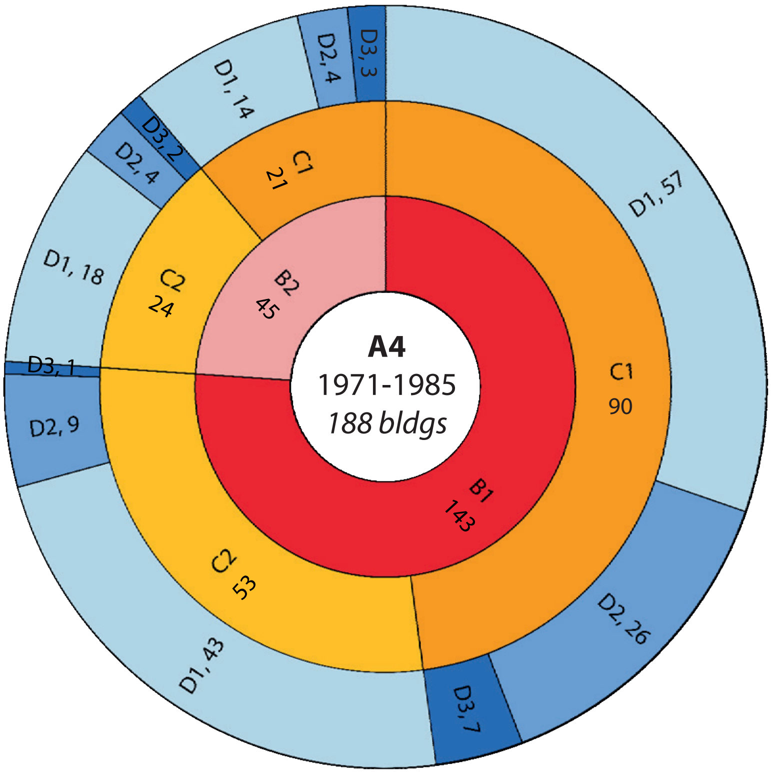


Figure 4-28. Sunburst diagram for construction period A4 (1971-1985).

Expressing the number of residential buildings for each intersection.

Nomenclature: B – Urban context (B1 – Isolated building, B2 – Adjacent building); C – Roof type (C1 – Flat roof, C2 – Sloped roof); D – Building height (D1 – 1-4 floors, D2 – 5-7 floors, D3 - > 7 floors).

Figure 4-29. Sunburst diagram for construction period A5 (1986-2005).

Expressing the number of residential buildings for each intersection.

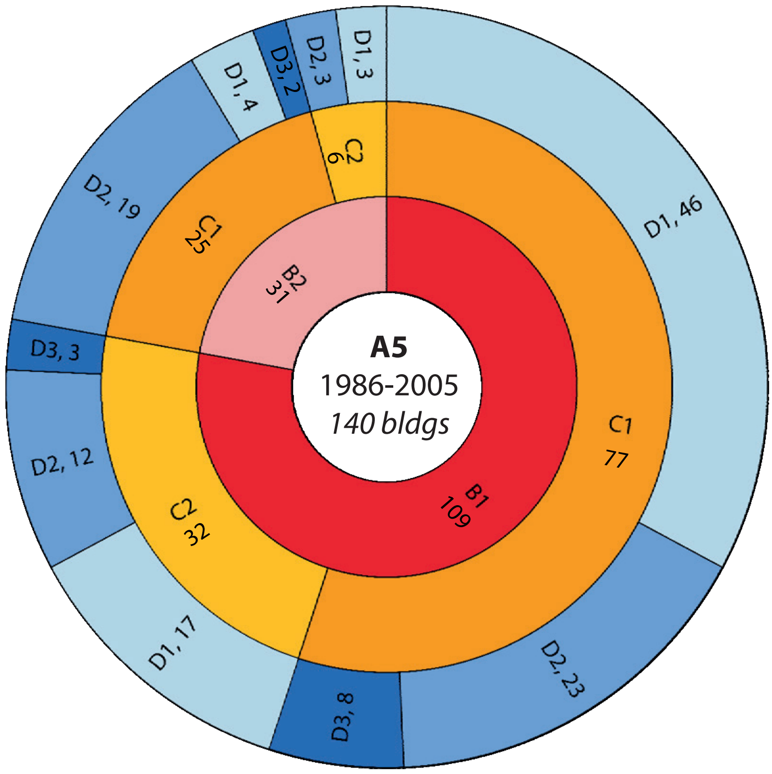


Figure 4-30 to Figure 4-34 illustrate each archetype's definition, derived by combining the dominant parameter values for each construction period. For example, Archetype 1 (Figure 4-30) represents an isolated (B1) building built before 1919, with a sloped roof (C2), between 5-7 floors (D2), of a level of protection II (E2; typical) and belonging to a small owner (F2).

As mentioned earlier, when analysing the results in Figure 4-19 to Figure 4-29, it is difficult in some cases to clearly identify the dominant value of each parameter, also since discrepancies are observed between number of buildings and floor area. The latter is mainly due to the variety in the height and the size of the buildings and the fact that some buildings present annex uses on the ground floor like a commercial activity.

In general, our approach has been to look at the weight of the parameters as a function of the number of buildings, but in cases of high discrepancy, we have chosen to leave more than one possibility in the definition of the archetype. This occurred especially for Archetypes 3, 4 and 5.

A - Construction period Archetype 1 | **< 1919** - **B1** - **C2** – **D1** - **E2**/E3 - **F2**/F3

before 1919	1919-1945	1946-1970	1971-1985	1986-2005

B - Urban context

B1: Isolated / detached building	B2: Adjacent building

C - Potential of surfaces (Roof)

Roof type

C1: Flat	**C2**: Sloped / Curved

D - Potential of surfaces (Facades)

Building height

D1: 1-4 floors (~5-14 m)	D2: 5-7 floors (~17-22 m)	D3: >7 floors (~>22 m)

E - Architectural quality / Level of protection

E1: I – Interesting / protected	**E2**: II - Typical / common	**E3**: III - Unattractive / disturbing

F - Type of owner

F1: Co-ownership (PPE)	**F2**: Small owner (<3 proprieties)	**F3**: Large owner (≥3 proprieties)

Archetype 1 definition, representing 238 buildings | 31% of residential buildings classified and built before 1919 (755 buildings).

Figure 4-30. Resulting criteria combination for Archetype 1, defined from Figure 4-25.

A - Construction period Archetype 2 | **1919-1945** - **B1** - **C2** – **D1** - **E2**/E3 - **F2**/F3

before 1919	1919-1945	1946-1970	1971-1985	1986-2005

B - Urban context

B1: Isolated / detached building | **B2**: Adjacent building

C - Potential of surfaces (Roof)

Roof type

C1: Flat | **C2**: Sloped / Curved

D - Potential of surfaces (Facades)

Building height

D1: 1-4 floors (~5-14 m) | **D2**: 5-7 floors (~17-22 m) | **D3**: >7 floors (~>22 m)

E - Architectural quality / Level of protection

E1: I – Interesting / protected | **E2**: II - Typical / common | **E3**: III - Unattractive / disturbing

F - Type of owner

F1: Co-ownership (PPE) | **F2**: Small owner (<3 proprieties) | **F3**: Large owner (≥3 proprieties)

Archetype 2 definition, representing 261 buildings | 54 % of residential buildings classified and built between 1919-1945 (482 buildings).

Figure 4-31. Resulting criteria combination for Archetype 2, defined from Figure 4-26.

A - Construction period Archetype 3 | **1946-1970** - **B1** - **C2** – **D1**/D2 - E2/**E3** - F2/F3

before 1919	1919-1945	1946-1970	1971-1985	1986-2005

B - Urban context

B1: Isolated / detached building | **B2**: Adjacent building

C - Potential of surfaces (Roof)

Roof type

C1: Flat | **C2**: Sloped / Curved

D - Potential of surfaces (Facades)

Building height

D1: 1-4 floors (~5-14 m) | **D2**: 5-7 floors (~17-22 m) | **D3**: >7 floors (~>22 m)

E - Architectural quality / Level of protection

E1: I – Interesting / protected | **E2**: II - Typical / common | **E3**: III - Unattractive / disturbing

F - Type of owner

F1: Co-ownership (PPE) | **F2**: Small owner (<3 proprieties) | **F3**: Large owner (≥3 proprieties)

Archetype 3 definition, representing 416 buildings | 56 % of residential buildings classified and built between 1946-1970 (735 buildings).

Figure 4-32. Resulting criteria combination for Archetype 3, defined from Figure 4-27.

A - Construction period Archetype 4 | **1971-1985** - **B1** – **C1** – **D1**/D2 - **E2** /E3– **F1**/F2/F3

before 1919	1919-1945	1946-1970	1971-1985	1986-2005

B - Urban context

B1: Isolated / detached building | **B2**: Adjacent building

C - Potential of surfaces (Roof)

Roof type

C1: Flat | **C2**: Sloped / Curved

D - Potential of surfaces (Facades)

Building height

D1: 1-4 floors (~5-14 m) | **D2**: 5-7 floors (~17-22 m) | **D3**: >7 floors (~>22 m)

E - Architectural quality / Level of protection

E1: I – Interesting / protected | **E2**: II - Typical / common | **E3**: III - Unattractive / disturbing

F - Type of owner

F1: Co-ownership (PPE) | **F2**: Small owner (<3 proprieties) | **F3**: Large owner (≥3 proprieties)

Archetype 4 definition, representing 83 buildings | 44 % of residential buildings classified and built between 1971-1985 (188 buildings).

Figure 4-33. Resulting criteria combination for Archetype 4, defined from Figure 4-28.

A - Construction period	Archetype 5 | **1986-2005** - **B1** – **C1** – **D1**/D2 - **E2**/E3 – **F1**/F2/F3			
before 1919	1919-1945	1946-1970	1971-1985	**1986-2005**

B - Urban context

B1: Isolated / detached building	B2: Adjacent building

C - Potential of surfaces (Roof)		D - Potential of surfaces (Facades)		
Roof type		Building height		
C1: Flat	C2: Sloped / Curved	**D1**: 1-4 floors (~5-14 m)	**D2**: 5-7 floors (~17-22 m)	D3: >7 floors (~>22 m)

E - Architectural quality / Level of protection

E1: I – Interesting / protected	**E2**: II - Typical / common	**E3**: III - Unattractive / disturbing

F - Type of owner

F1: Co-ownership (PPE)	**F2**: Small owner (<3 proprieties)	**F3**: Large owner (≥3 proprieties)

Archetype 5 definition, representing 69 buildings | 49 % of residential buildings classified and built between 1986-2005 (140 buildings).

Figure 4-34. Resulting criteria combination for Archetype 5, defined from Figure 4-29.

4.6. Synthesis

The top-down analysis presented in this chapter serves to gather an understanding of the residential building stock of the city of Neuchâtel and to define archetypal situations that ensure selecting relevant case studies for the next steps of the research.

Since buildings considered as typical (classified as category II or III according to the Architectural Heritage Service of Neuchâtel) can be found in any city of the Swiss Plateau, by focusing on such buildings, the potential of application of the results of the thesis in other contexts is ensured, conditional to considering the particularities of the specific project on which the architects wish to apply the method.

A - Construction period	before 1919	1919-1945	1946-1970	1971-1985	1986-2005
B - Urban context	Adj. / isolate	Isolated	Isolated	Isolated	Isolated
C – Roof potential	Sloped	Sloped	Sloped / Flat	Flat	Flat
D – Façade potential	5-7 floors	1-4 floors	5-7 floors	5-7 floors	5-7 floors
E - Architectural quality (heritage)	Typical II	Typical II	Typical II	Typical II	Unattractive III
	Arch. 1	**Arch. 2**	**Arch. 3**	**Arch. 4**	**Arch. 5**

Figure 4-35 summarises the parameter value combinations leading to the five archetype definitions. As these definitions do not characterise a fully-defined building, the next phase, described in the following chapter, is to select a representative building of each archetype, in order to carry out a series of real case studies.

5. Selection and analysis of representative buildings

This chapter is dedicated to the selection and description of the five case studies based on the study of the residential building stock in the city of Neuchâtel and the archetypal definition proposed in Chapter 4.

5.1. Identification of five case studies

To identify case studies, we use the archetypal definitions presented in Phase 1 and the collected data organised in the geographic information system (GIS) platform QGIS [**OSGeo 2018**]. In addition, we make use of a list of buildings owned by two of the ACTIVE INTERFACES research project partners [**Active Interfaces 2018**], a pension fund (prevoyance.ne) and the city of Neuchâtel.

These buildings have been selected and classified according to the archetypes definition and the following excluding features: the buildings are already renovated, they are classified as category I – protected, considered as too singular and thus presenting an added difficulty at the time of being renovated, they are situated in the historical city centre, they are only partially residential or they belong to multiple owners.

In addition to considering the archetype definitions, each of the possible buildings has been pre-analysed in order to prioritise the buildings with a current status similar to the original one.

It is important to highlight that this is not entirely possible since, in general, some maintenance work has been required (without the presence of an architect having a global strategy for the building), such as window replacement. In any case, this punctual replacement of construction elements, as we will see in the description of the selected buildings, does not mean that they cannot be replaced again according to the renovation strategy proposed to achieve the 2050 targets.

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A preview of the selected case studies corresponding to the different archetypal situations is shown in Figure 5-1, and their full description is presented in the following section. Figure 5-2 shows an overview with the location of the different case studies corresponding to the five archetypal situations. The selected buildings offer a variety of urban situations that will help architects who want to apply the results of this thesis to find the reference or references that best fit their own project.

In order to define the E0-Current status of each case study including its constructive characteristics, a visit was made to each building and a historical contextualisation was carried out with respect to the evolution of the energy regulations (Figure 5-3) **[archiwatt 2006]** and the main construction periods in Switzerland **[Perez 2014]**. This allows us to have a better idea of the logic with which the buildings were built and under what type of regulations.

	Arch. 1	**Arch. 2**	**Arch. 3**	**Arch. 4**	**Arch. 5**
A - Construction period	before 1919	1919-1945	1946-1970	1971-1985	1986-2005
B - Urban context	Isolated	Isolated	Isolated	Isolated	Isolated
C – Roof potential	Sloped	Sloped	Flat	Flat	Flat
D – Façade potential	5-7 floors	1-4 floors	5-7 floors	> 7 floors	5-7 floors
E - Architectural quality (heritage)	Typical II	Typical II	Typical II	Typical II	Unattractive III
					
Address	Rue de Beauregard 1	Rue du Rocher 25	Rue du Chasselas 2-6	Rue des Troncs 12-14	Route de Pierre-à-Bot 34
Owner			prévoyance.ne		City of Neuchâtel

Figure 5-1. Final selection of the different case studies with their corresponding combination of values for the selection parameters.

As can be seen in Figure 5-3, the main regulations related to the energy performance of buildings began to appear with the oil crisis of 1973. The first standard with the aim of reducing energy consumption in buildings is the SIA 180/1. It was introduced in 1977, but was not fully implemented on the entire Swiss territory until 1983. The SIA standards with the most impact on buildings performance were published in 1988 (380/1, 180/1, 238, 243 and 279) and progressively implemented until 1993. In that same year, the first Swiss Energy Law **[AFCF 2018]** was published, where a global vision is proposed for the entire territory and all economic sectors.

Likewise, in 1994, two researchers **[Kesselring et al. 1994]** from the Paul Scherrer Institute in Villigen (Switzerland) proposed for the first time the 2'000-Watts Society concept under the idea of allowing the development of the most disadvantaged countries and inviting the most advanced countries to reduce their primary energy consumption.

Among the selected buildings, only Archetype 5 was built under the application of the standards published in 1988. Archetype 4 built in 1972-73 and designed in the middle of the oil crisis (1973) already presents certain timid measures, such as the 4 centimetres of insulation inside the concrete prefabricated elements that make up the façade.

Through this analysis, we can intuit that most of the buildings available to us likely have a very high energy consumption and are urgently in need of a renovation.

Figure 5-2. Location of the selected case studies on the map of Neuchâtel.

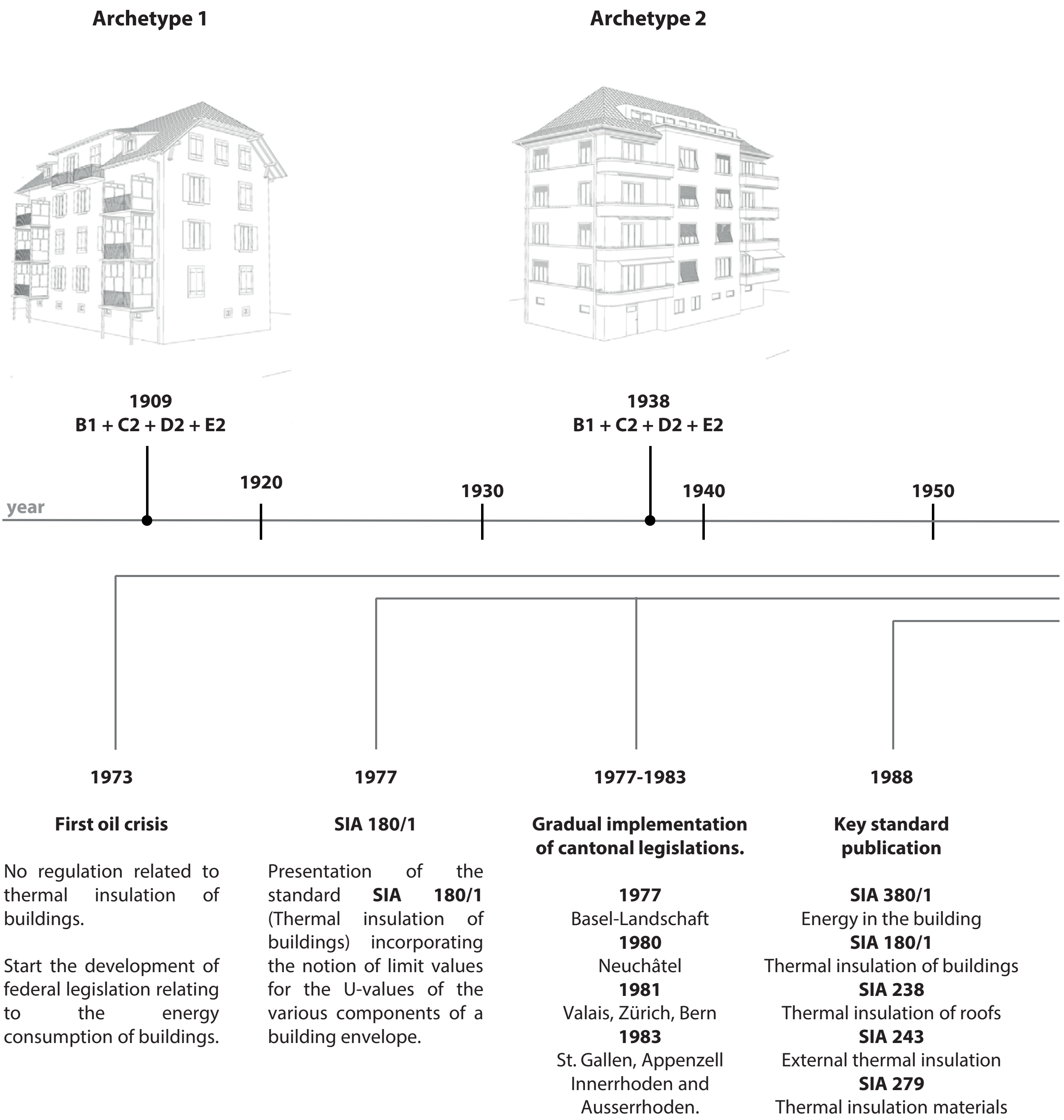


Figure 5-3. Appearance of the different regulations related to the energy performance of buildings during the period from 1919 to 2001 and situation of the archetypes **[archiwatt 2006]**.

Archetype 3

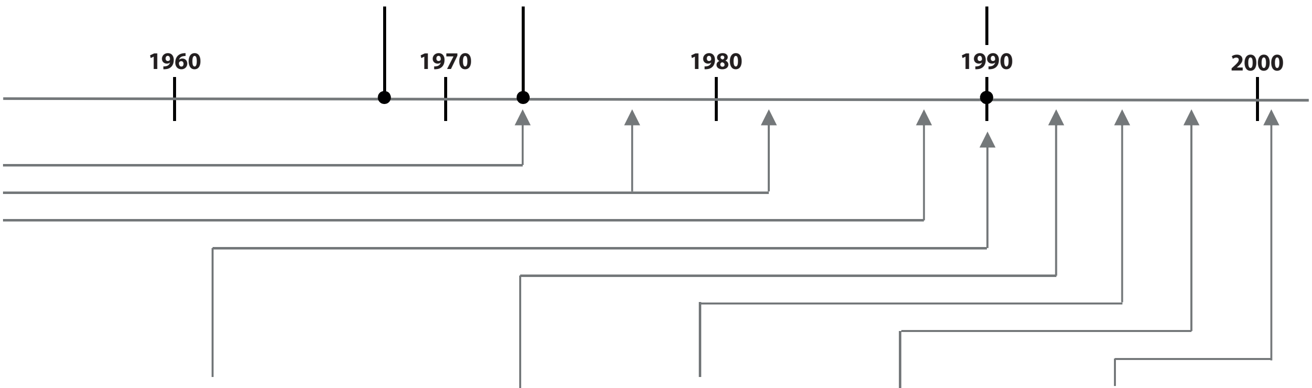
1968
B1 + C1 + D2 + E2

Archetype 4

1972-73
B1 + C1 + D3 + E2

Archetype 5

1990
B1 + C2 + D2 + E2



1990

Launch of the Swiss Solar Prize

State of play of cantonal legislation relating to the thermal insulation of buildings in force in 1990:
No prescriptions in 4 cantons.
SIA 180/1 implemented in 11 cantons.
SIA 180/1 reinforced in 3 cantons.
SIA 180/1 and SIA 380/1 implemented in 3 cantons
SIA 380/1 implemented in 5 cantons

1993

Implementation of the first Swiss Energy Law.

1994

2000-Watt society concept

Concept proposed by two scientists Kesselring and Winter.

1995

SIA 380/4

Publication of **SIA 380/4** (Electrical energy in buildings).

1997

Switzerland ratifies the Kyoto Protocol.

1st Swiss House Fair and MINERGIE® label.

2001

New SIA 380/1

Publication of the revised **SIA 380/1** standard (Energy in the building) including the adaptation to the European standard EN 832 - 2000 (Thermal behavior of buildings. Calculation of energy needs for heating. Residential buildings).

5.2. Selection and analysis workflow

Here is presented the part of the global workflow (Figure 5-4) concerning Phase 2 of the methodology. Prior to the upcoming phases where renovation scenarios are developed and assessed, it is necessary to know the current status of the buildings in terms of energy performance. This knowledge is acquired through a diagnosis going from the analysis of the energy bills (historical consumption) to the dynamic energy simulation using a detailed energy model (that will subsequently allow testing the implementation of different improvement strategies).

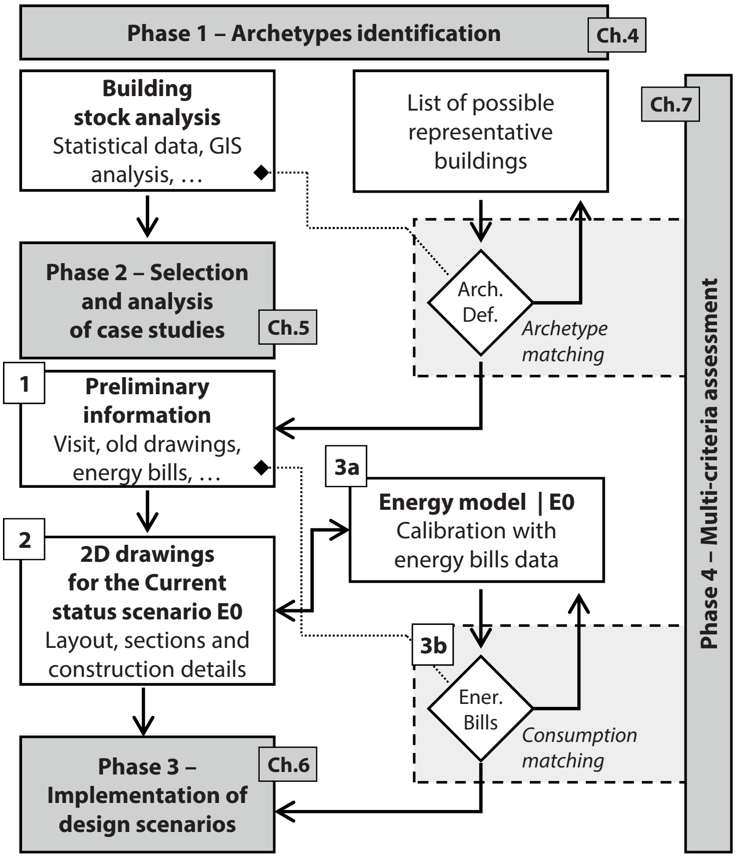


Figure 5-4. Global workflow illustrating the links between Phase 2 and the other Phases 1, 3 and 4.

The process starts with Step 1: analysing the preliminary information obtained for each selected building, including the visit, the original drawings of the building and the available energy bills (electricity, gas and oil) provided by the owner, completing the missing information with values from [**Giebeler et al. 2011; Perez 2014**], according to the construction period of each building.

Step 2 mainly consists in preparing all necessary graphical information for defining the characteristics of the building envelope. For each archetype, we obtain the thermal transmittance (U-value) including an estimation of linear thermal bridges (LTB) for the different parts of the envelope using reference values from the Swiss catalogue of thermal bridges [**Infomind Sàrl 2003**]. Detailed information about the physical characteristics of material used, the calculation method and the results of the LTB analysis can be found in Annexe 10.1. Despite the fact that the impact of LTB in the current status of the building is almost negligible due to the high U-values, we consider interesting to still take into account the LTB.

This information is used as input data to configure the energy model in step 3a. This energy model is built in the DesignBuilder software [**DesignBuilder 2018]** using, in addition to the constructive details gathered in the previous steps, the normative assumptions and user profiles for multi-family buildings provided by the SIA 2024:2015 [**SIA 2015a**], including occupancy schedules, standard utilisation profiles, etc. These assumptions are detailed in Annexe 10.2.

The use of normed user profiles allows to overcome uncertainties about how to set the simulation parameters, but also allows to easily compare results from different buildings by isolating the user behaviour issue [**Jad 2014**]. In addition, results can be compared with those obtained with software like LESOSAI [**E4tech 2018]**, which uses the same values from SIA 2024:2015.

Following an iterative process, the energy model is calibrated (step 3b) using real energy consumption values obtained from recent energy bills, a recommended step allowing to minimise the performance gap throughout the next phases of the methodology [**Sanguinetti 2012; De Wilde 2014; Jad 2014**]. The calibration of the model basically consists in adapting some simulation parameters for which we do not have the exact information (e.g. airtightness) based on existing literature **[Perez 2014]**. Further details on this procedure can be found in Chapter 7, Section 7.2.2.

In the following sections, the analysis of the E0-Current status is described for each case study, followed by the comparison between the results of the hourly-timestep simulation in terms of final energy for heating and the real consumption (obtained via the energy bill provided by the building's owner). The *"calibrated"* energy model is later used to implement the different renovation scenarios (Chapter 6).

5.3. Description and analysis of five selected case studies

5.3.1. Archetype 1

Description of case study building

Archetype 1, built in 1909, dwelling house constructed by the architect C. Philippin for Edouard Basting, merchant (trade of wood). In 1938, installation of bathrooms on each floor by Jacques Béguin, architect, on behalf of the real estate company Beauregard 1. Currently the building is owned by a pension fund (prévoyance.ne) (Figure 5-5). This building is not specially protected; it is classified by the heritage department of Neuchâtel as Category II [**Neuchâtel 2005**], i.e. typical or picturesque building. The quasi total absence of decorative elements is to emphasise. It is located on ancient vineyard terraces, and is part of a set of three identical standalone buildings (non-adjacent to other buildings).

There is a ground floor, three upper floors and an attic, for a total of 5 floors. The main façade is south facing. The sloped roof presents two sides facing north and south. There are two apartments per floor, except for the ground floor, which is dedicated to cellar spaces, laundry room and the facility spaces with an oil-boiler for heating and domestic hot water (DHW).

The north façade (access and street side) has a sober appearance with small vertical openings, symmetrical composition, median axis marked by the entrance with windows illuminating the stairwell space.

The south façade (lake side) presents eminently vertical openings that punctuate the symmetrical composition of the façade with two rows of balconies supported by columns. All openings are composed of natural stone framing to emphasise the outline of the windows, the rest of the façade is finished with plaster.

Figure 5-5. Image of E0-Current status scenario, Archetype 1.

Main characteristics of the building (Figure 5-5 to Figure 5-7):

- Total floor area: 788.5 m^2 (Energy Reference Area – ERA: 630.8 m^2).
- Sloped roof (uninsulated), wood structure and terracotta colour ceramic tiles.
- Monolithic walls in rubble masonry walls and exterior plaster (40-50 cm depending on the floor) without insulation.
- Wooden frame windows with single glazing and exterior wooden shutters.
- Balconies with reinforced concrete slab with metal profiles and supported by metal columns. Metal railings. The last floor has small balconies but with the same constructive logic.
- The slab of the first floor (against the ground floor space) is built in hollow slabs, the remaining 4 floors are built with wooden beams embedded in the façades and resting on walls in the centre of the building.
- An oil boiler covers the heating and DHW demand.

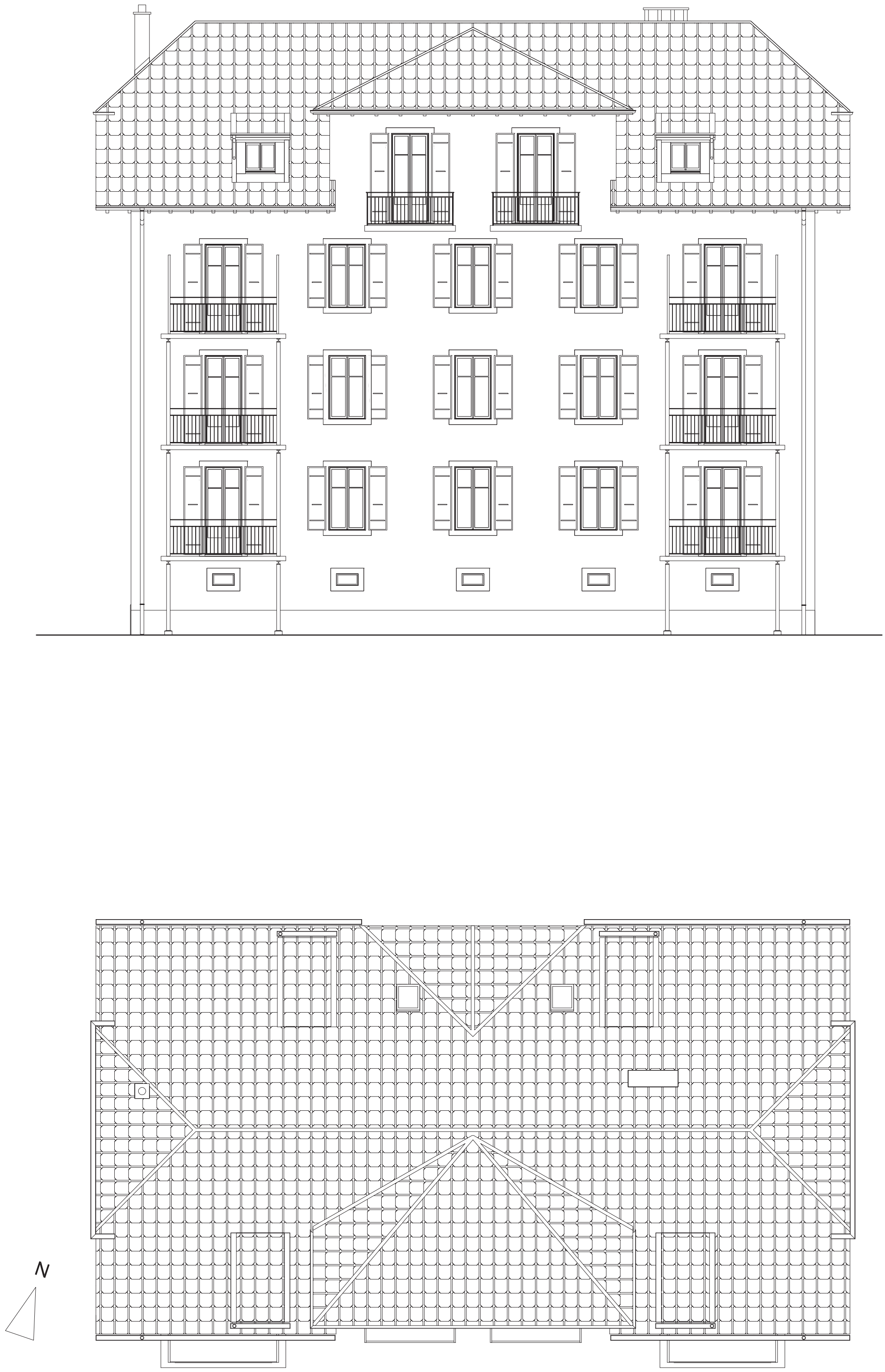


Figure 5-6. Façade and roof plan for Archetype 1.

5 4 3 2 1 0m

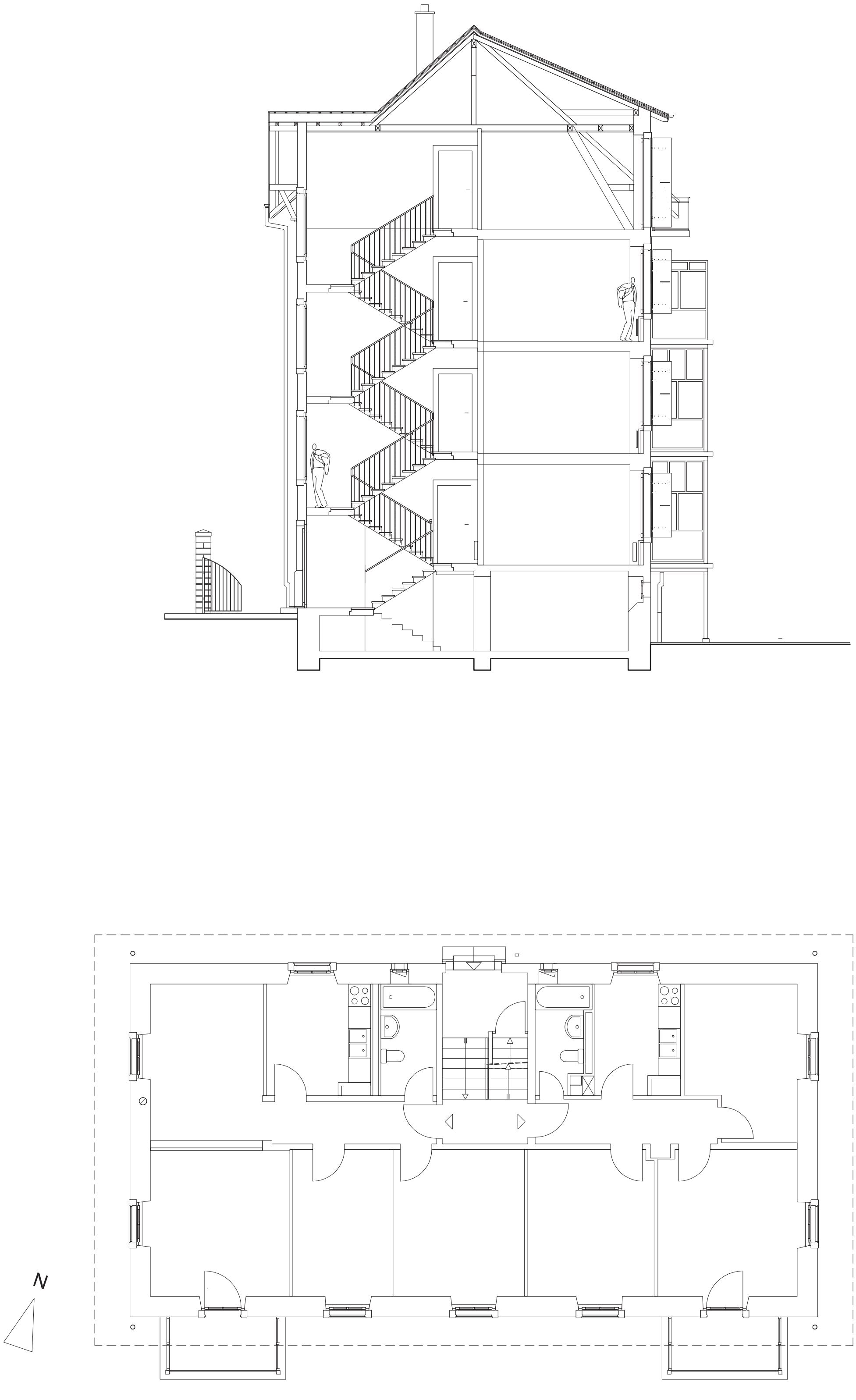


Figure 5-7. Section and floor plan for Archetype 1.

5 4 3 2 1 0 m

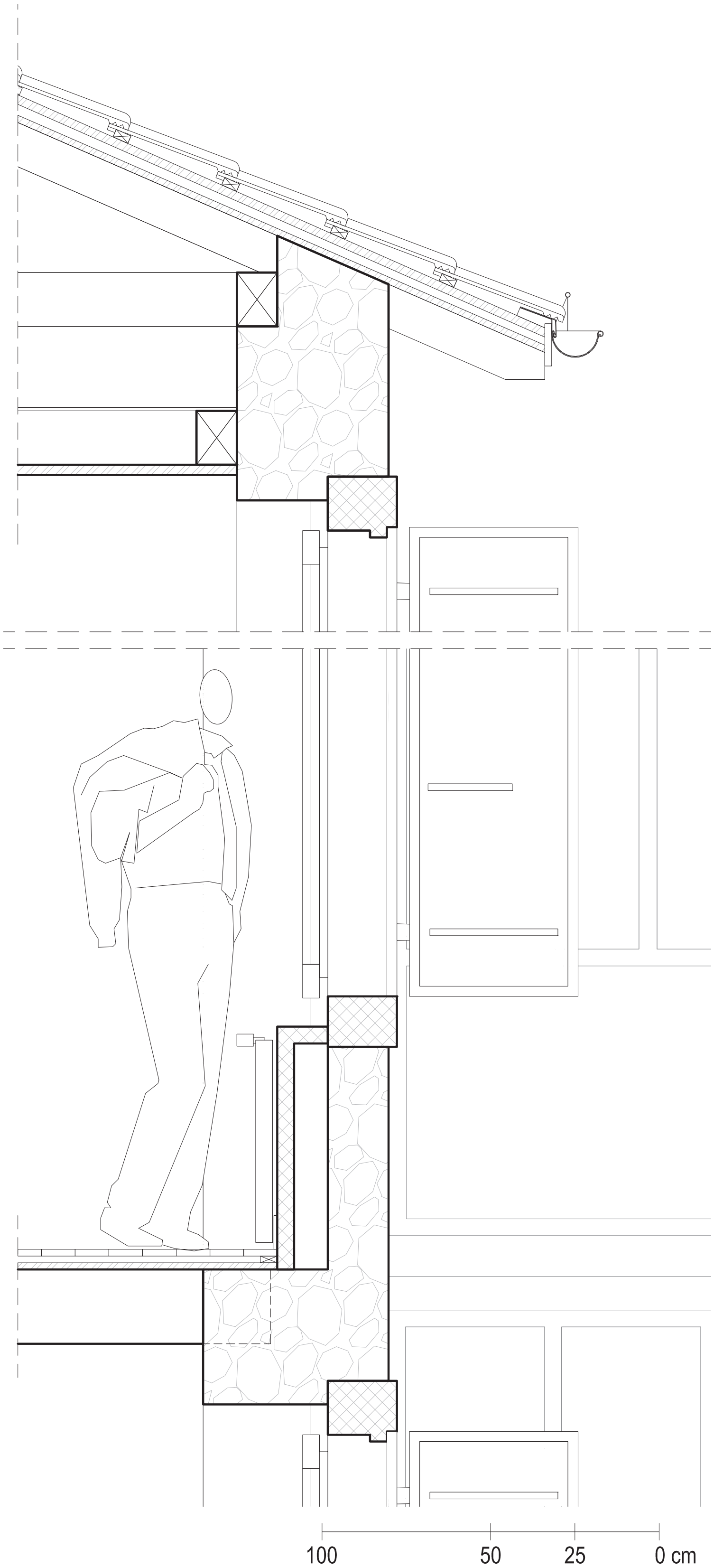


Figure 5-8. Façade and roof constructive detail, **E0 – Current Status**, Archetype 1.

Roof: Tiles and slats 8 cm, Hardboard 0.6 cm, Oak lathing 5 cm, Solid wood 1.5 cm.

Façade: Exterior plaster 2 cm, Rubble masonry 40 cm, Gypsum plaster 1cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement mortar 3 cm, Hallow slab / concrete 20 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cast concrete slab 20 cm.

Solar protections: Wooden shutter 3cm.

Balconies: Cement slabs 12 cm, Metallic profiles IPE 100.

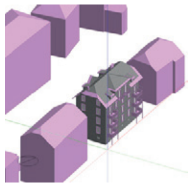
Openings: Wooden frame windows with single-glazing 6 mm.

Calibrated energy model

Building envelope characteristics

Table 5-2 shows a summary of the configuration values regarding the building envelope considering the constructive details for Archetype 1 (Figure 5-8), and a comparison of annual heating demand between the calibrated energy model simulation result and the energy bills provided by the owner for the years 2013, 2014 and 2015.

Table 5-2. Summary of configuration data of the energy model and comparison between simulated and real heating demand for Archetype 1, scenario E0-Current status. Using data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.3.

Archetype 1	U-Value	Energy model image
Roof*	1.59 W/m²·K	
Façade*	1.07 W/m²·K	
Internal floor*	0.94 W/m²·K	
External Floor (ground)*	1.74 W/m²·K	
Openings (glazing)**	5.70 W/m²·K	
Infiltration rate	2.00 ACH	
Occupation rate	0.0342 m²/person	
Annual energy demand comparison [kWh/ m²·year]		
	Energy bill $_{(2013-2015)}$	Calibrated energy model
Heating demand (Oil)	186 kWh/ m²·year	189 kWh/ m²·year

Thermal bridges estimation

Table 5-3 shows the values adopted for each type of LTB, using reference values from the Swiss catalogue of thermal bridges **[Infomind Sàrl 2003]**.

Table 5-3. Linear thermal bridges for Archetype 1 according to **[Infomind Sàrl 2003]**. Detailed information in Annexe 10.1.3.

Type	Linear thermal bridge (LTB) description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	3.2-A1	-0.03
TB2	Wall-Unheated ground floor	3.4-A2	+0.19
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I2	+0.15
TB6	Wall-Floor (Ext – balcony)	1.1-A1/A3	+1.05
TB7	Blind box	4.2-A1	+0.26
TB8	Still below window	5.1-A1	+0.12
TB9	Jamb at window or door	5.2-A1	+0.17
TB10	Lintel above window or door	5.3-A1	+0.20

5.3.2. Archetype 2

Description of case study building

Archetype 2, designed and built by architect O. Roulet in 1938. It is located on ancient vineyard terraces. It is a standalone, symmetrical, sober and traditional building with modernist vocabulary (Figure 5-9).

This building is not specially protected; it is classified by the heritage department of Neuchâtel as Category II [**Neuchâtel 2005**], i.e. typical or picturesque building.

Absence of decorative elements, except a cornice (strip forming continuous tablet) in yellow coloured cement continuously surrounding the four façades, thus accentuating the continuity between the façades and reinforcing the horizontal character of the building.

The openings have embrasures and shelves in stone imitation with a typical external wooden roller shutter. Almost all the original windows (wood and single glazing) have been replaced by wooden frames with double glazing.

The balconies, semi-loggias, are made with a concrete platform and railings in plastered masonry topped with a metal handrail. In the corners, the dynamic expression of the cantilevered rounded balconies reinforces the continuity between the façades.

The sloped-roof supported by a wooden structure presents four-sides in which are located an attic space with two apartments.

The ground floor is composed of a limestone masonry wall with small openings for ventilation purposes. At this level we have cellar spaces, laundry room and facility spaces with a gas-boiler for heating and DHW.

The rest of the floors present a monolithic façade consisting of hollow bricks finished with plaster. The floors are made with joists and terracotta slabs.

The north façade has a central forepart marking the presence of the stairwell naturally lit by a bay window. The entrance is protected by a canopy.

The south façade has a central front, pierced by windows equipped with a typical external wooden roller shutters, which gives a verticality to the whole.

Figure 5-9. Image of E0-Current status scenario, Archetype 2.

Main characteristics of the building (Figure 5-9 to Figure 5-12):

- Total floor area: 847.2 m^2 (Energy Reference Area – ERA: 713.8 m^2).
- Sloped roof (uninsulated), wood structure and terracotta colour ceramic tiles.
- Monolithic walls in hollow bricks and exterior plaster (35 cm) without insulation.
- Wooden frame windows with single glazing and external wooden roller shutters.
- Balconies, semi-loggias, made with a concrete platform, railings in plastered masonry and metallic handrail.
- The slab of the five floors is built with joists and terracotta slabs.
- A gas boiler covers the heating and DHW demand.

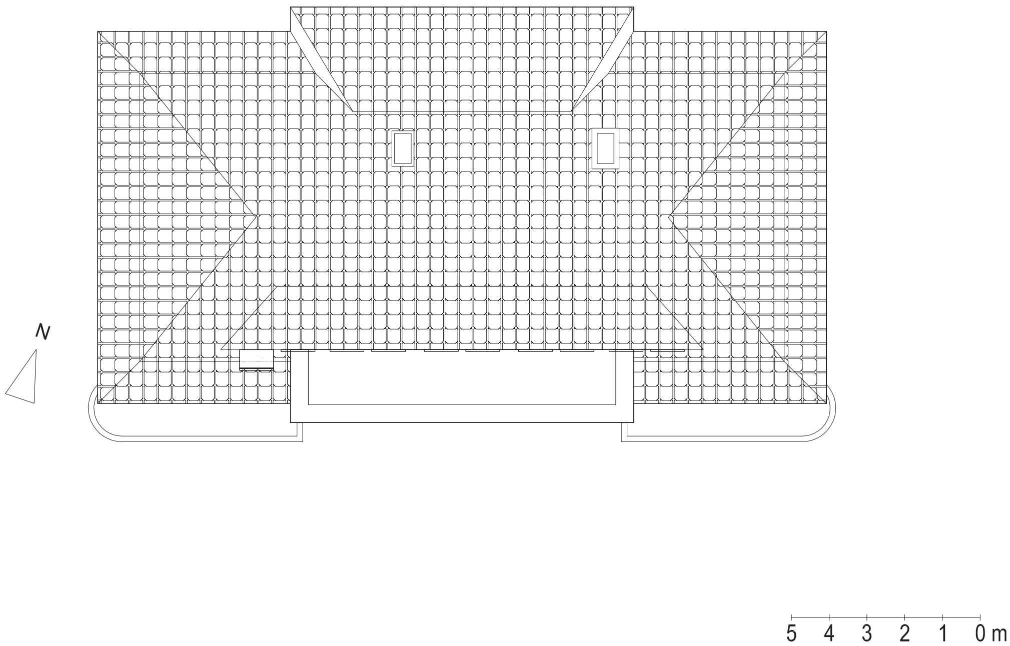
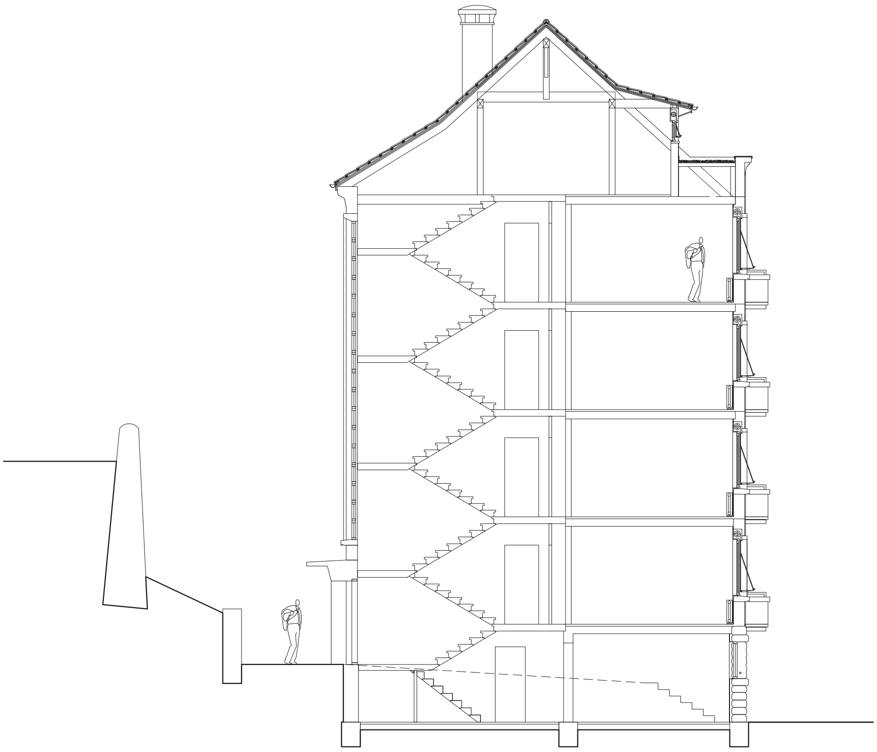


Figure 5-10. Façade and roof plan for Archetype 2.



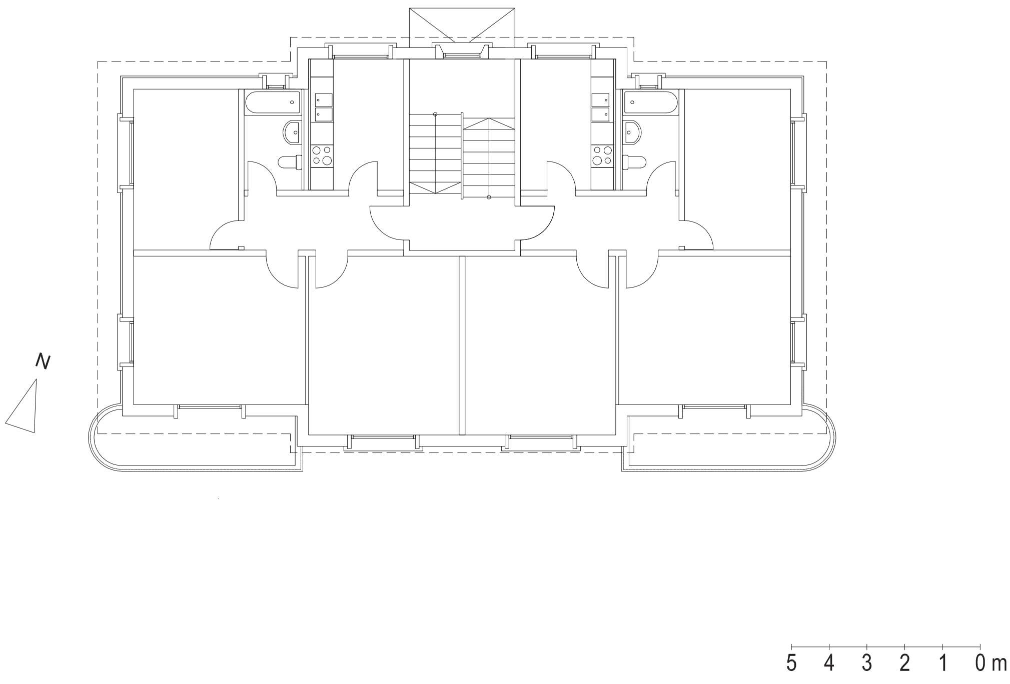


Figure 5-11. Section and floor plan for Archetype 2.

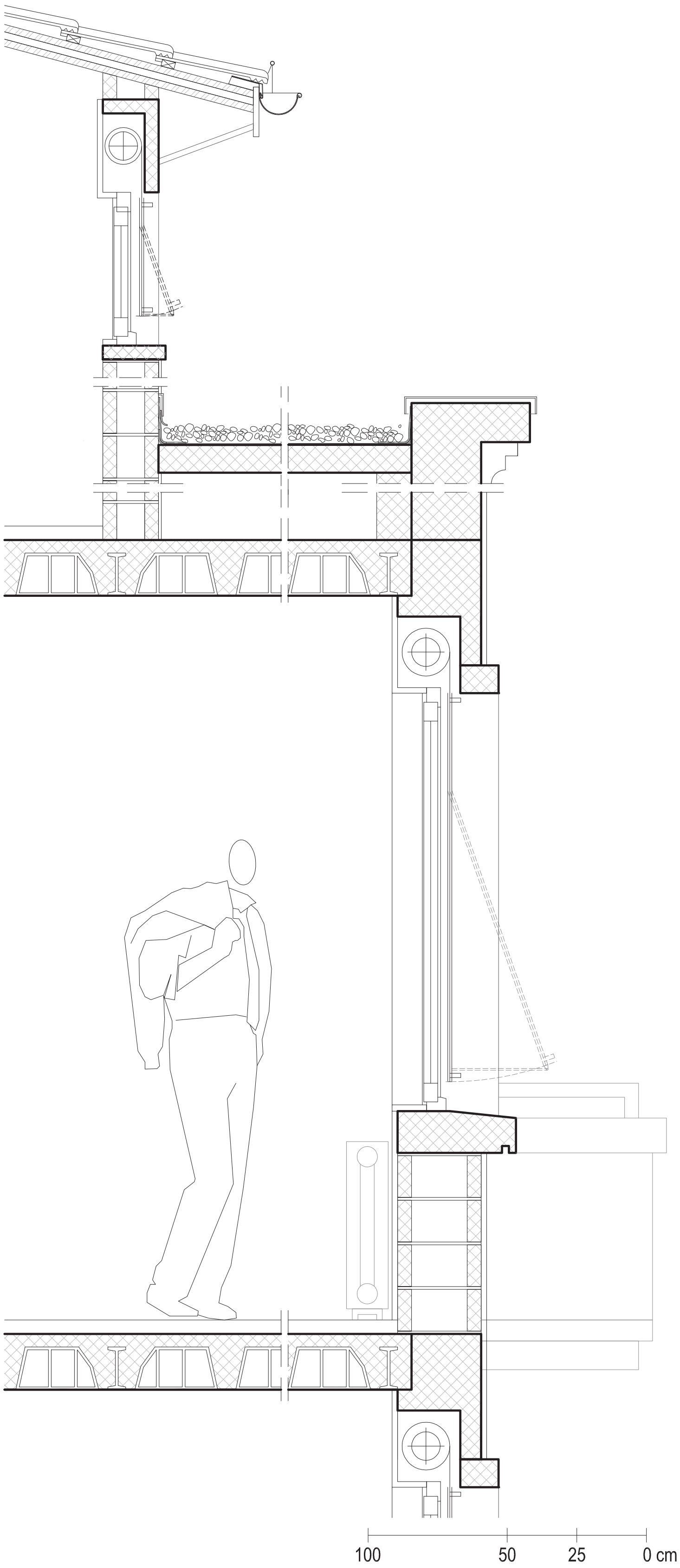


Figure 5-12. Façade and roof constructive detail, **E0 – Current Status**, Archetype 2.

Roof: Tiles and slats 5 cm, Hardboard 2.5 cm, Oak lathing 5 cm, Hardboard 2.5 cm.

Façade: Exterior plaster 2 cm, Cement hollow bricks masonry 35 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 5 cm, Vapour barrier, Cement mortar 3 cm, Joists and terracotta slab 20 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cement mortar 3 cm, Cast concrete slab 15 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Cement slabs 18 cm.

Openings: Wooden frame windows with single-glazing 6 mm.

Calibrated energy model

Building envelope characteristics

Table 5-4 shows a summary of the configuration values regarding the building envelope considering the constructive details for Archetype 2 (Figure 5-12), and a comparison of annual heating demand between the calibrated energy model simulation result and the energy bills provided by the owner for the years 2013, 2014 and 2015.

Table 5-4. Summary of configuration data of the energy model and comparison between simulated and real heating demand for Archetype 2, scenario E0-Current status. Using data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.4.

Archetype 2	U-Value	Energy model image
Roof*	0.93 W/m²·K	
Façade*	1.13 W/m²·K	
Internal floor*	1.06 W/m²·K	
External Floor (ground)*	1.63 W/m²·K	
Openings (glazing)**	5.70 W/m²·K	
Infiltration rate	2.00 ACH	
Occupation rate	0.0364 m²/person	
Annual energy demand comparison [kWh/ m²·year]		
	Energy bill $_{(2013\text{-}2015)}$	Calibrated energy model
Heating demand (Gas)	165 kWh/ m²·year	163.2 kWh/ m²·year

Thermal bridges estimation

Table 5-5 shows the values adopted for each type of LTB, using reference values from the Swiss catalogue of thermal bridges **[Infomind Sàrl 2003]**.

Table 5-5. Linear thermal bridges for Archetype 2 according to **[Infomind Sàrl 2003]**. Detailed information in Annexe 10.1.4.

Type	Linear thermal bridge (LTB) description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	3.2-I1	-0.07
TB2	Wall-Unheated ground floor	3.4-I2	-+0.01
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I2	+0.15
TB6	Wall-Floor (Ext – balcony)	1.1-I1	+1.05
TB7	Blind box	4.2-A1	+0.26
TB8	Still below window	5.1-I3	+0.17
TB9	Jamb at window or door	5.2-I1	+0.11
TB10	Lintel above window or door	5.3-I4	+0.19

5.3.3. Archetype 3

Description of case study building

Archetype 3, built in 1968, presents a simple and rational architecture in plastered masonry, with a horizontal composition where windows and loggias are set back from the exterior façade plane. The building is part of a large bar whose total length is 57.5 meters and width is 13 meters (Figure 5-13).

Typical building of the 60's, standalone (non-adjacent to other buildings), with a south-east main orientation. It is a building composed of three units with independent entrances. It has a concrete flat roof without insulation, finished by 5 cm of gravel.

This building is not specially protected; it is classified by the heritage department of Neuchâtel as Category II **[Neuchâtel 2005]**, i.e. typical or picturesque building.

The building has 7 floors (ground floor + 6) and a whole basement (under-ground) with cellar space, laundry room and technical facilities.

It is located on a sloped terrain, a contention wall side street (north-west façade) allows a direct access to the 4th floor. This building's organisation allows to make good use of the inclined ground. The access is made via three bridges in reinforced concrete from the street side wall, three floors are under the street level (street side).

The internal organisation allows to have south / north crossing apartments and small studios facing south-east. At the extremes, the apartments have two bedrooms with a large living room, those in the centre have two bedrooms, and there are one-bedroom studios. All apartments have a loggia open on the lake side, all included inside the volume of the building.

The windows have PVC frames and low-performance double glazing. There are external roller shutters, mounted in an interior box without insulation creating a thermal bridge.

The railing on the south-east façade of the loggias is continuous, giving a very marked horizontality to the façade. The north façade uses the same trick to emphasise horizontality, only cut by a bay window that naturally illuminates the stairwell.

Main characteristics of the building (Figure 5-13 to Figure 5-17):

- Total floor area: 4'415 m^2 (Energy Reference Area – ERA: 4'210 m^2).
- Flat roof without insulation, reinforced concrete, cement screed and gravel.
- 30 cm plastered façade with load-bearing perforated-brick on the outside, air gap and brick on the inside.
- The windows were replaced in 2000 by PVC frames and low-performance double glazing, the original windows had metal frames and single glazing.
- The railing of the loggias, continuous along the façade, is crowned with a tablet made of aluminium sheet and gives a very marked horizontality to the whole.
- 14 cm reinforced concrete slabs, 1 cm insulation and 4 cm cement screed.
- This building has a central condensing gas boiler (from 2008) covering heating and DHW demand.

Figure 5-13. Image of E0-Current status scenario, Archetype 3.

Main characteristics of the building (Figure 5-13 to Figure 5-17):

- Total floor area: 4’415 m^2 (Energy Reference Area – ERA: 4’210 m^2).
- Flat roof without insulation, reinforced concrete, cement screed and gravel.
- 30 cm plastered façade with load-bearing perforated-brick on the outside, air gap and brick on the inside.
- The windows were replaced in 2000 by PVC frames and low-performance double glazing, the original windows had metal frames and single glazing.
- The railing of the loggias, continuous along the façade, is crowned with a tablet made of aluminium sheet and gives a very marked horizontality to the whole.
- 14 cm reinforced concrete slabs, 1 cm insulation and 4 cm cement screed.
- This building has a central condensing gas boiler (from 2008) covering heating and DHW demand.

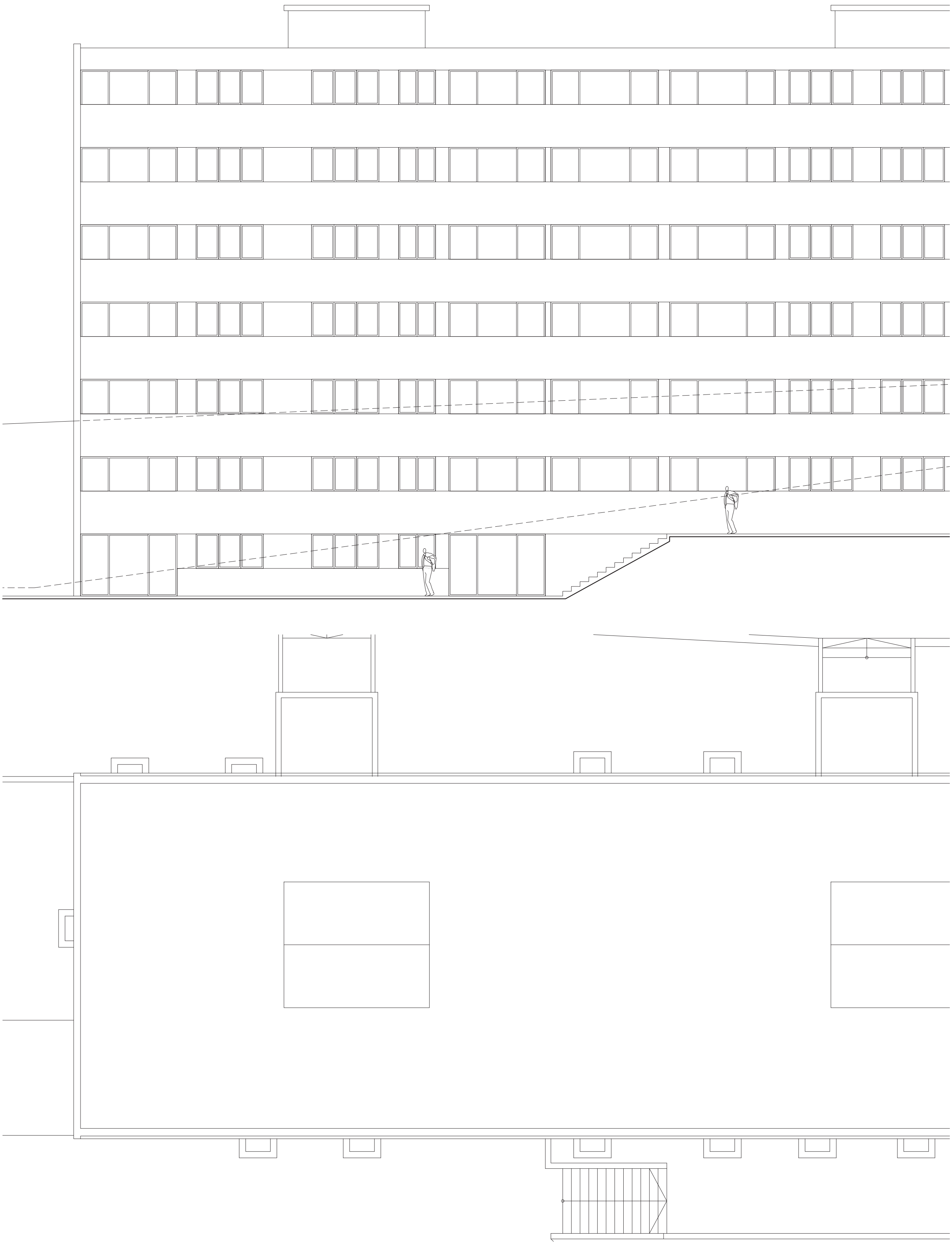
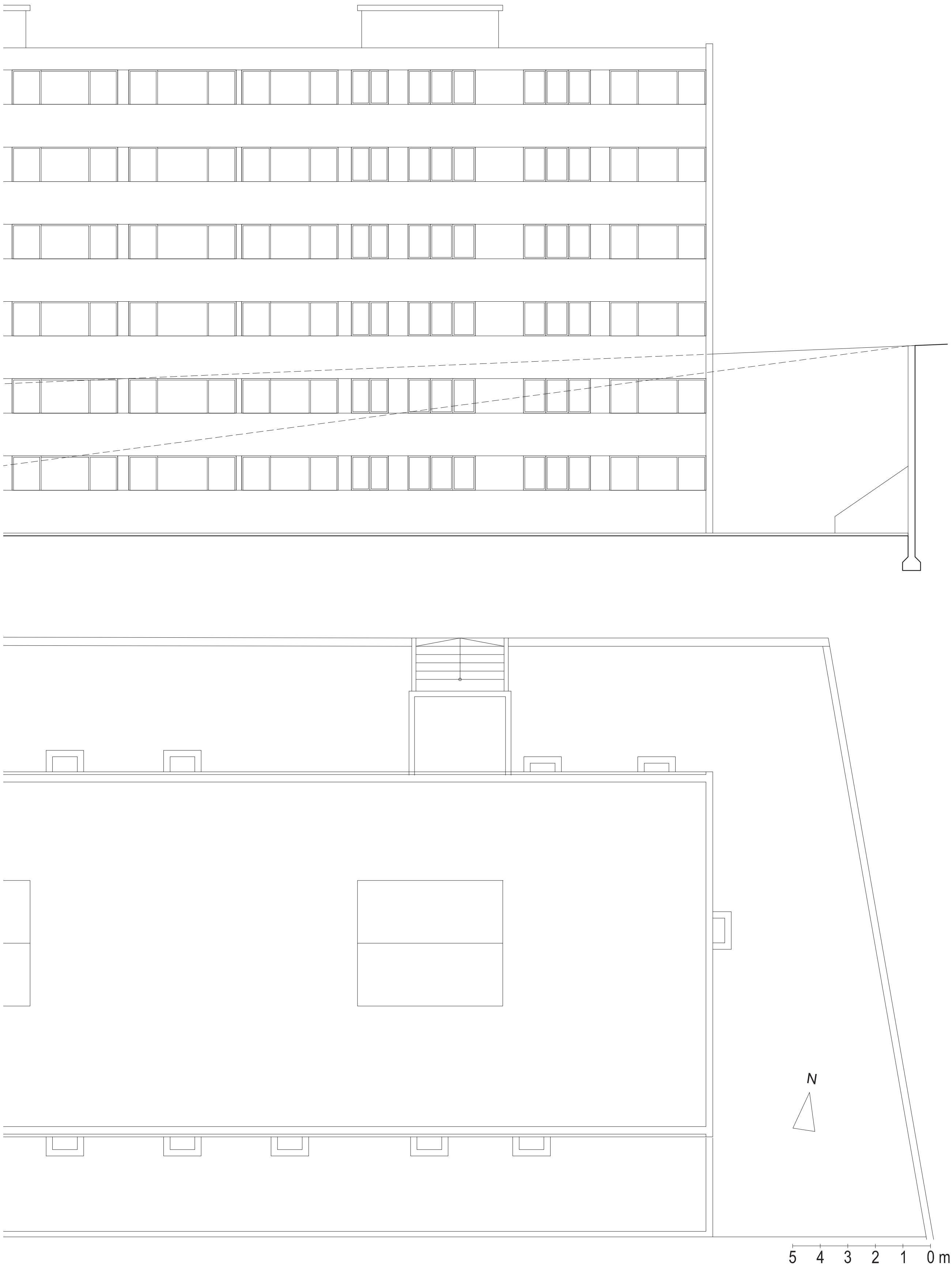


Figure 5-14. Façade and roof plan for Archetype 3.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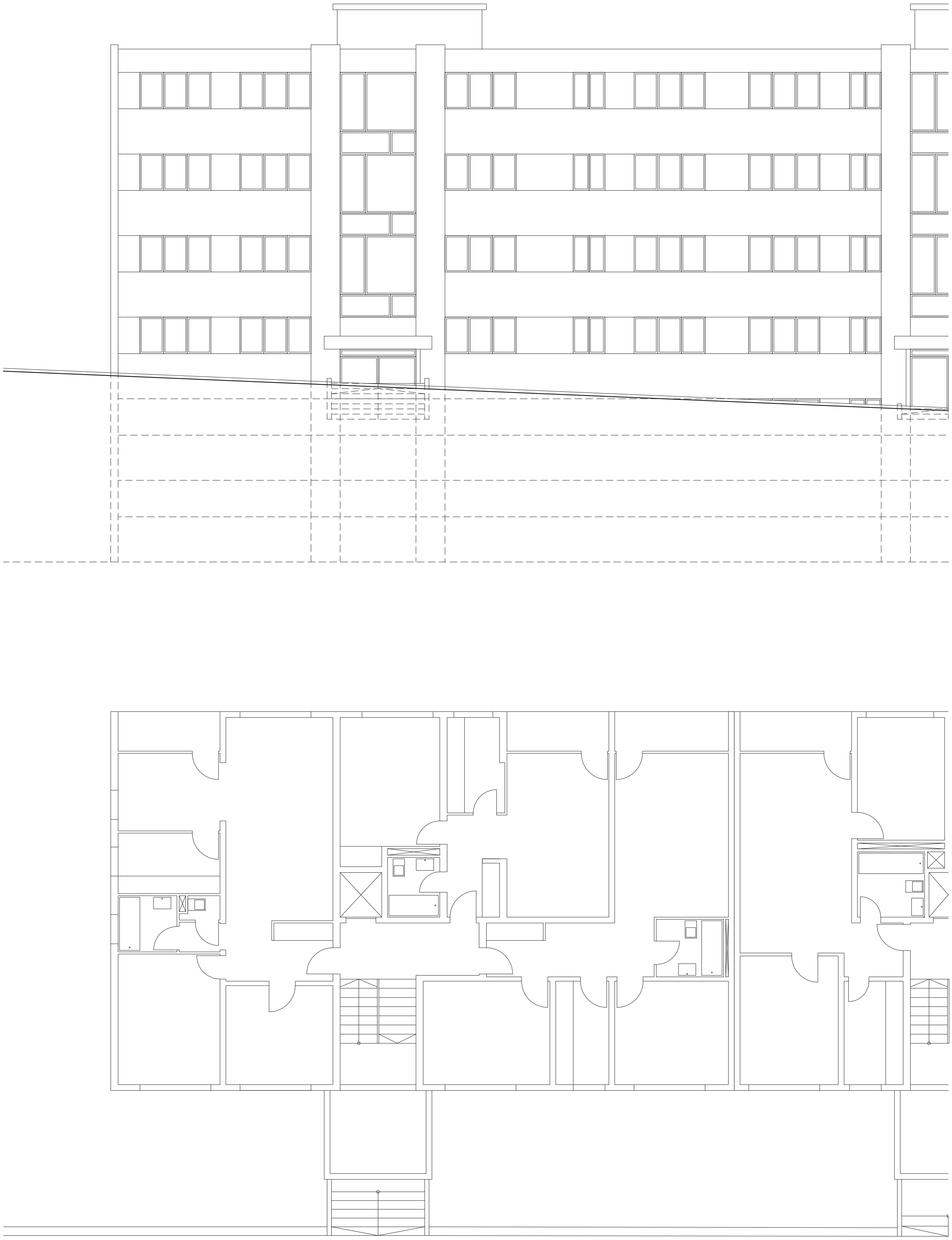
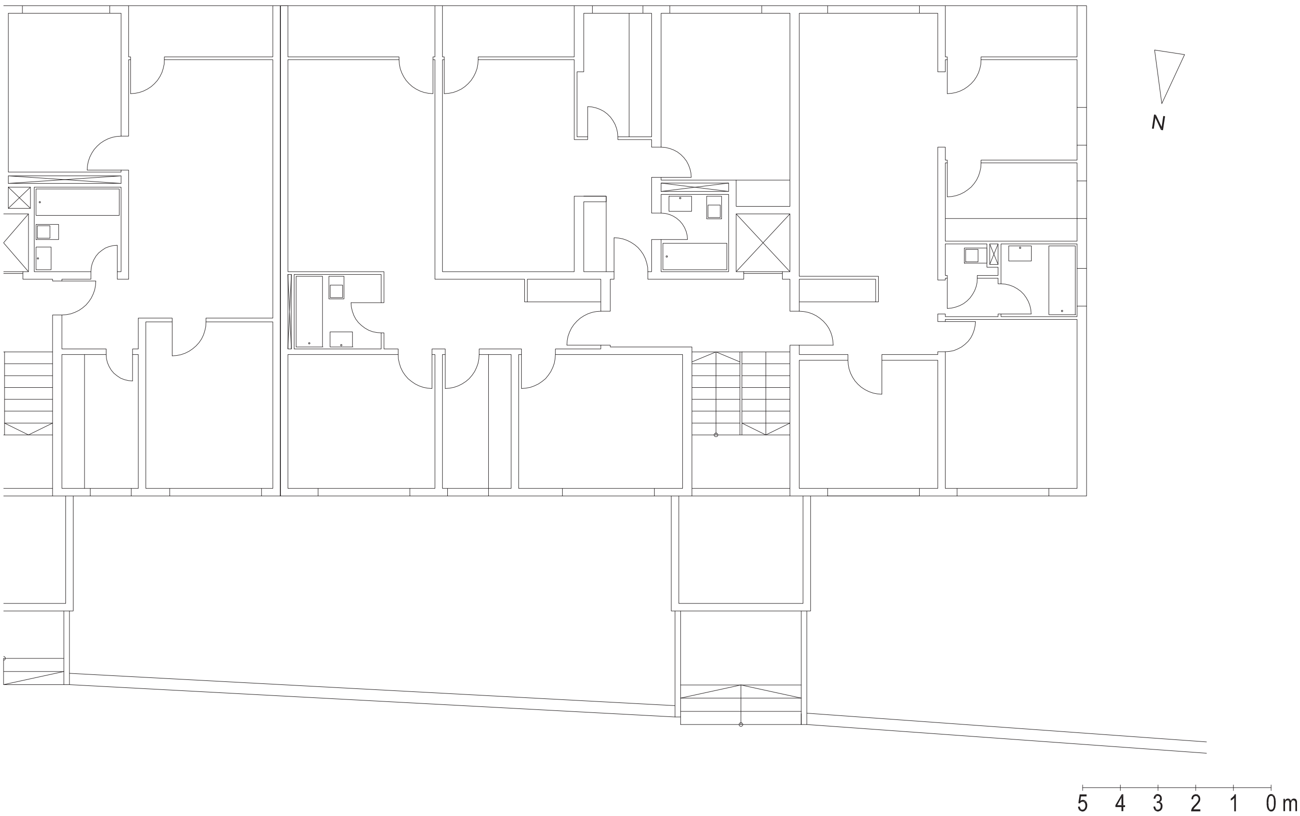


Figure 5-15. Façade and floor plan for Archetype 3.


N
5 4 3 2 1 0 m

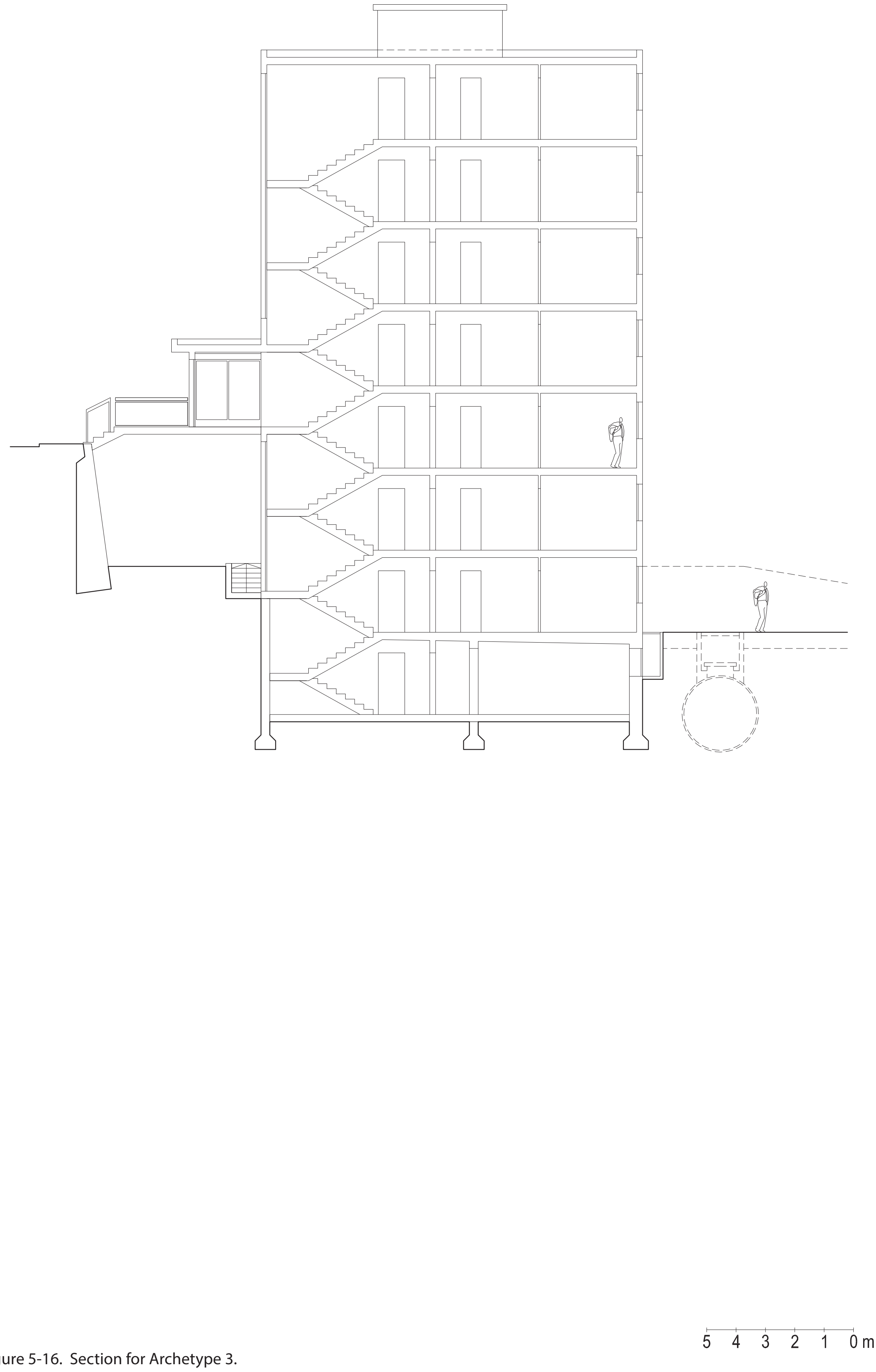


Figure 5-16. Section for Archetype 3.

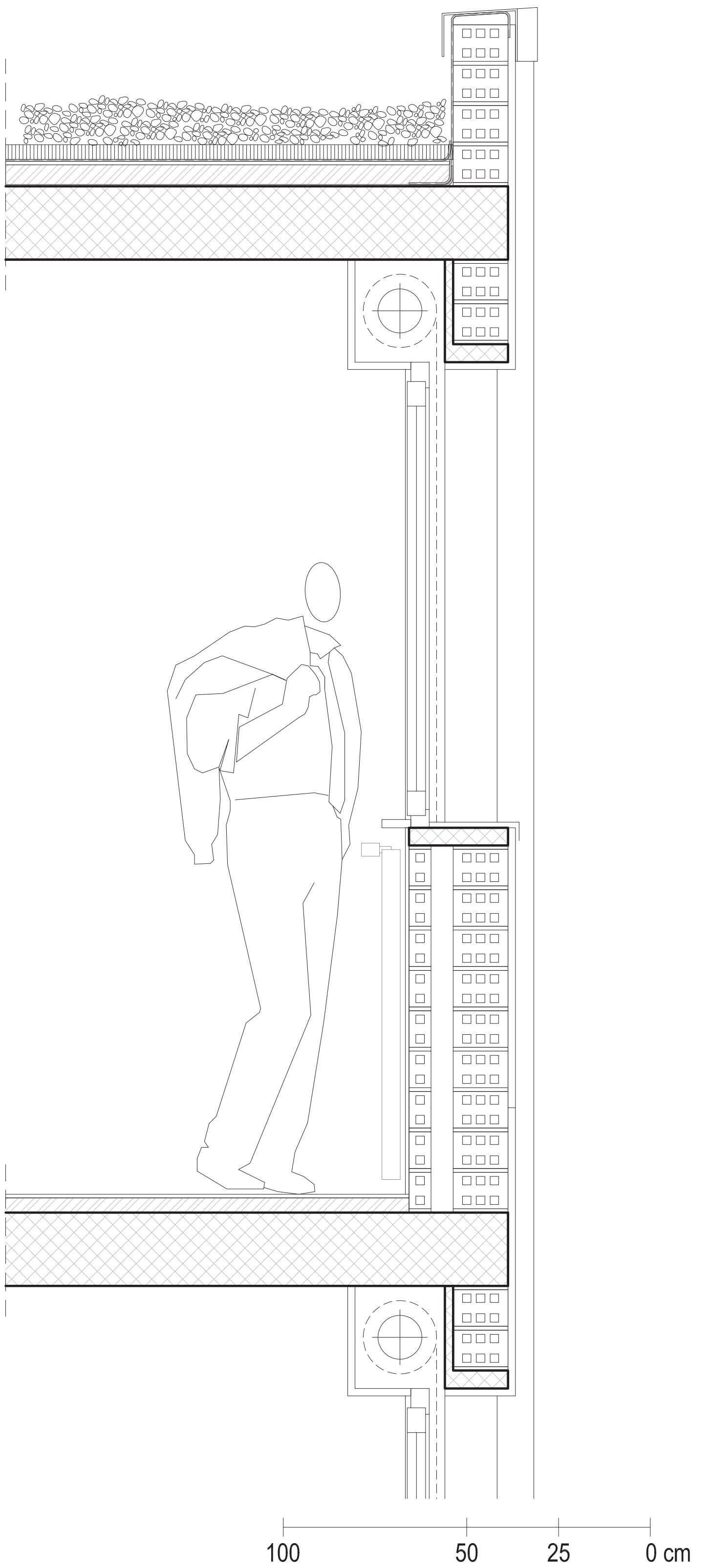


Figure 5-17. Façade and roof constructive detail, **E0 – Current Status**, Archetype 3.

Roof: Gravel 5-10 cm, Bitumen 0.4 cm, EPS expanded polystyrene (old) 4 cm, Bitumen 0.4 cm, Reinforced concrete slab 20 cm.

Façade: Exterior plaster 2 cm, Ceramic brick 15 cm, Air gap 6 cm, Ceramic brick 6 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 5 cm, Cement screed 3 cm, Reinforced concrete slab 20 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Reinforced concrete slab 20 cm, XPS extruded polystyrene 4 cm.

Solar protections: Wooden roller shutter 3 cm. Balconies: Reinforced concrete slab 20 cm.

Openings: Wooden frame windows with single-glazing 6 mm.

Calibrated energy model

Building envelope characteristics

Table 5-6 shows a summary of the configuration values regarding the building envelope considering the constructive details for Archetype 3 (Figure 5-17), and a comparison of annual heating demand between the calibrated energy model simulation result and the energy bills provided by the owner for the years 2014 and 2015.

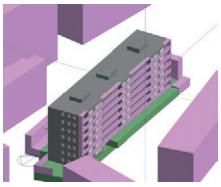
Archetype 3	U-Value	Energy model image
Roof*	0.91 W/m^2·K	
Façade*	1.18 W/m^2·K	
Internal floor*	1.06 W/m^2·K	
External Floor (ground)*	0.60 W/m^2·K	
Openings (glazing)**	5.70 W/m^2·K	
Infiltration rate	2.00 ACH	
Occupation rate	0.0347 m^2/person	
Annual energy demand comparison [kWh/ m^2·year]		
	Energy bill $_{(2014\text{-}2015)}$	Calibrated energy model
Heating demand (Gas)	137 kWh/ m^2·year	132.9 kWh/ m^2·year

Table 5-6. Summary of configuration data of the energy model and comparison between simulated and real heating demand for Archetype 3, scenario E0-Current status. Using data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.5.

Thermal bridges estimation

Table 5-7 shows the values adopted for each type of LTB, using reference values from the Swiss catalogue of thermal bridges **[Infomind Sàrl 2003]**.

Type	Linear thermal bridge (LTB) description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	1.3-A6	-0.04
TB2	Wall-Unheated ground floor	3.4-A1	+0.24
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.84
TB7	Blind box	4.2-A1	+0.26
TB8	Still below window	5.1-A1	+0.15
TB9	Jamb at window or door	5.2-A1	+0.17
TB10	Lintel above window or door	5.3-A1	+0.16

Table 5-7. Linear thermal bridges for Archetype 3 according to **[Infomind Sàrl 2003]**. Detailed information in Annexe 10.1.5.

5.3.4. Archetype 4

Description of case study building

Archetype 4, built in 1972-73, is a multi-family residential building with the typical architecture of a construction period in full growth, which corresponds to the second part of the *"thirty glorious"* (1961-1975). This large-scale project was therefore carried out at the beginning of the oil crisis (1972-1976), whose influence is slightly reflected in the thermal considerations on the design of the building envelope (Figure 5-18).

This building is not specially protected; it is classified by the heritage department of Neuchâtel as Category II **[Neuchâtel 2005]**, i.e. typical or picturesque building.

It has 11 stories, consisting of 52 apartments and 5'263 m^2 of living floor area. The structure consists of reinforced concrete slabs and loading walls, stabilised by a vertical circulation core.

It has a poorly insulated envelope, with façades made of prefabricated concrete elements. They are composed by sandwich elements with an interior load-bearing wall with 14 cm of reinforced concrete, 4 cm of expanded polystyrene insulation (XPS) and exposed concrete of varying thickness covered with a crushed stone agglomerate.

It presents a subtle play of façade elements enriched on the south-east and south-west façades by loggias. These façades are composed of sand-coloured repetitive elements and the bevelled concrete openings bring some lightness and plasticity and a globally balanced expression.

The wood-metal openings show signs of obvious wear. Inlet and low insulating power of the glazing. Degraded interior and exterior surfaces, malfunctioning of the openings. Significant sealing problems of the interior blind boxes. Degraded roller blinds, partly damaged fittings, to be replaced in case of replacement of windows.

The flat roof at the level of the attic forms a terrace and a technical space. It has only 10 cm of insulation plus 4 cm of concrete outdoor floor tiles, resulting from a renovation carried out 15 years ago.

The state of general deterioration of accessible and inaccessible roof parts is very advanced. Several punctual maintenance interventions by a company expert in sealing repairs allowed to limit the damage. Unheated spaces are not insulated compared to apartments.

Figure 5-18. Image of E0-Current status scenario, Archetype 4.

Main characteristics of the building (Figure 5-18 to Figure 5-23):

- Total floor area: 5’263 m^2 (Energy Reference Area – ERA: 5’093 m^2).
- Façades composed of prefabricated concrete elements (sandwich) anchored at the top of the slab with 4 cm of EPS insulation.
- Reinforced concrete slabs and walls, stabilised by a vertical circulation core.
- Poorly insulated flat roof composed by 22 cm of reinforced concrete slab, 6 cm of expanded polystyrene (EPS) insulation, and 5 cm of gravel.
- Windows with wood-metal frame and double glazing, very damaged.
- This building has a central oil boiler covering heating and DHW demand.

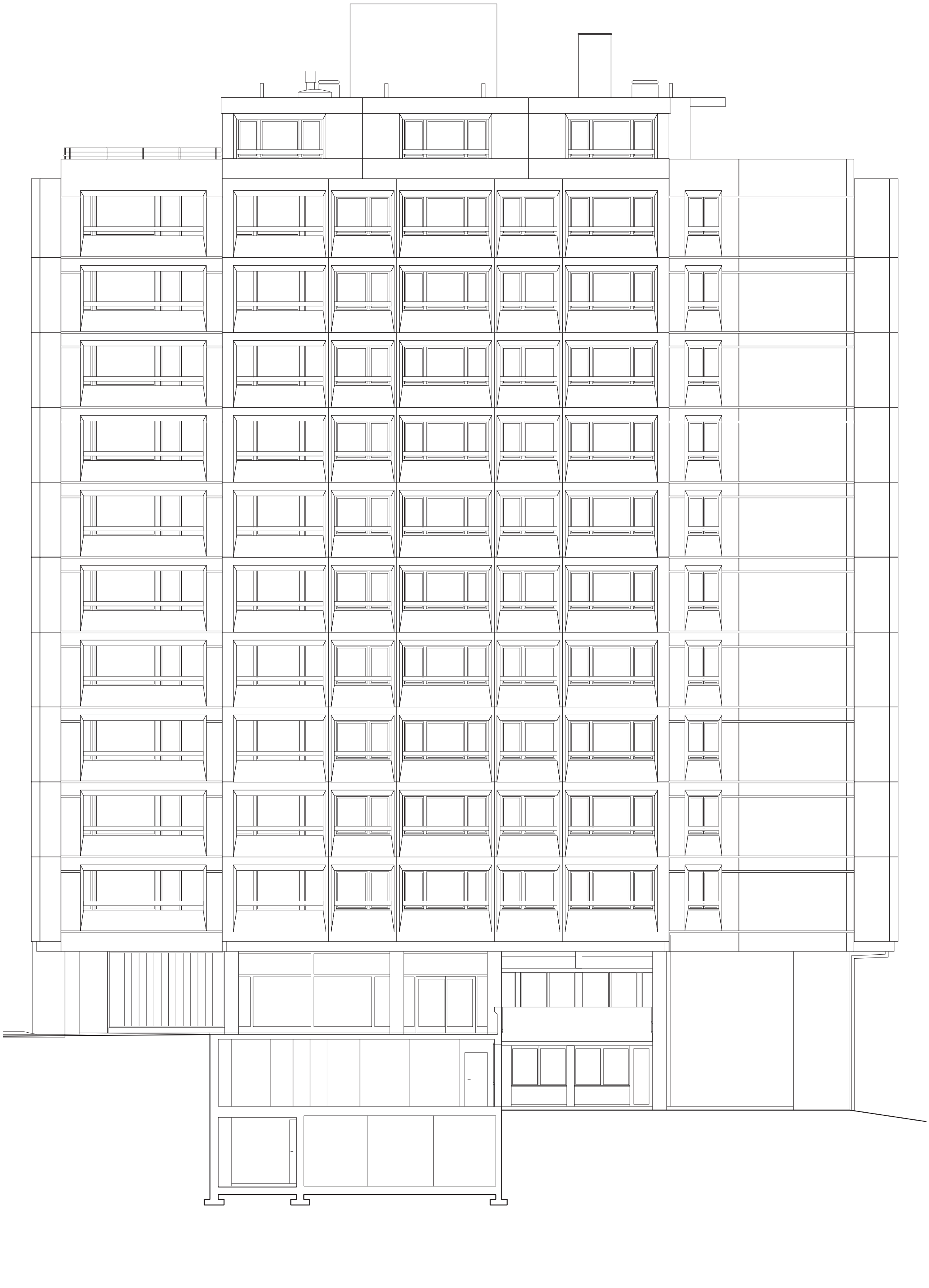


Figure 5-19. South-west façade for Archetype 4.

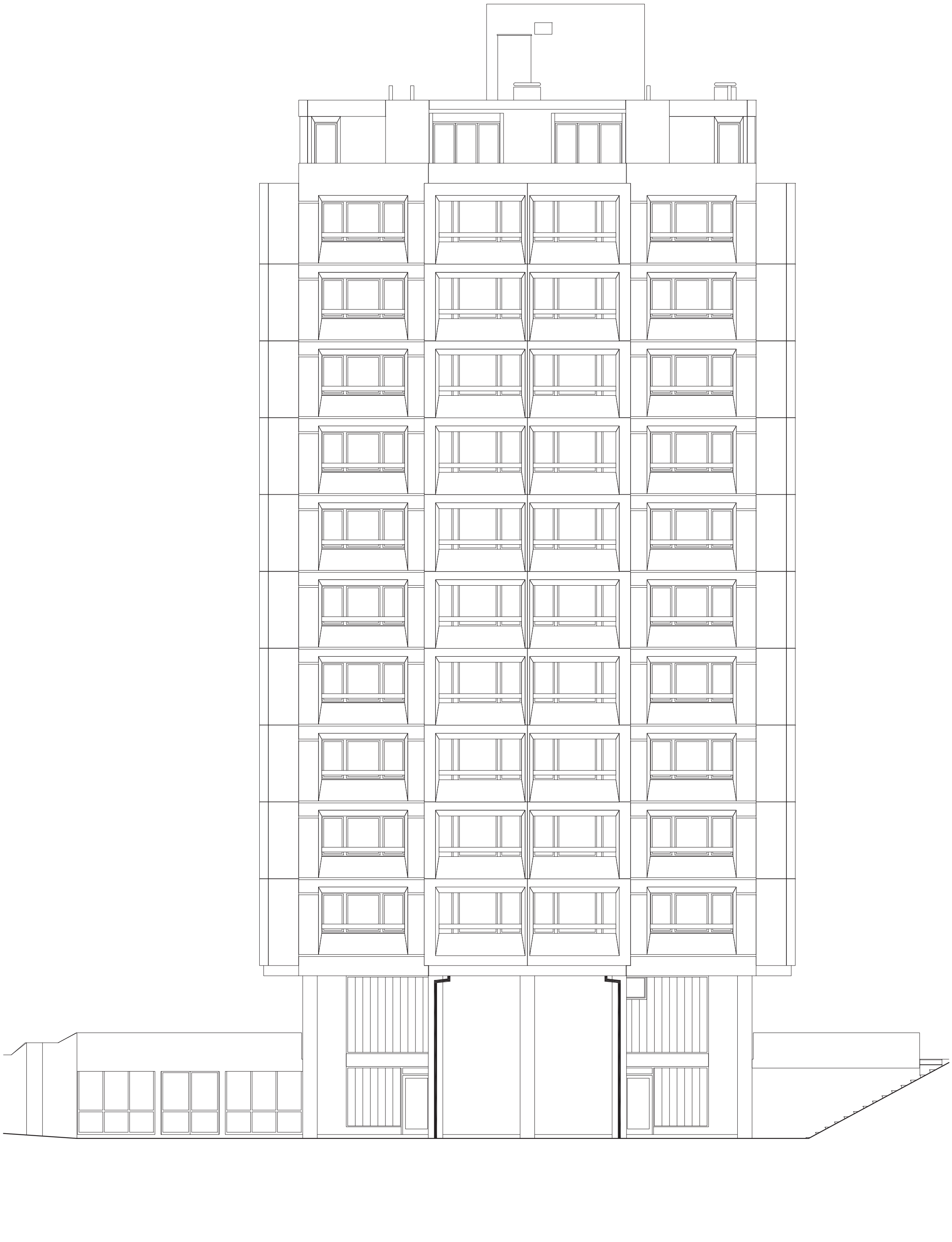


Figure 5-20. South-east façade for Archetype 4.

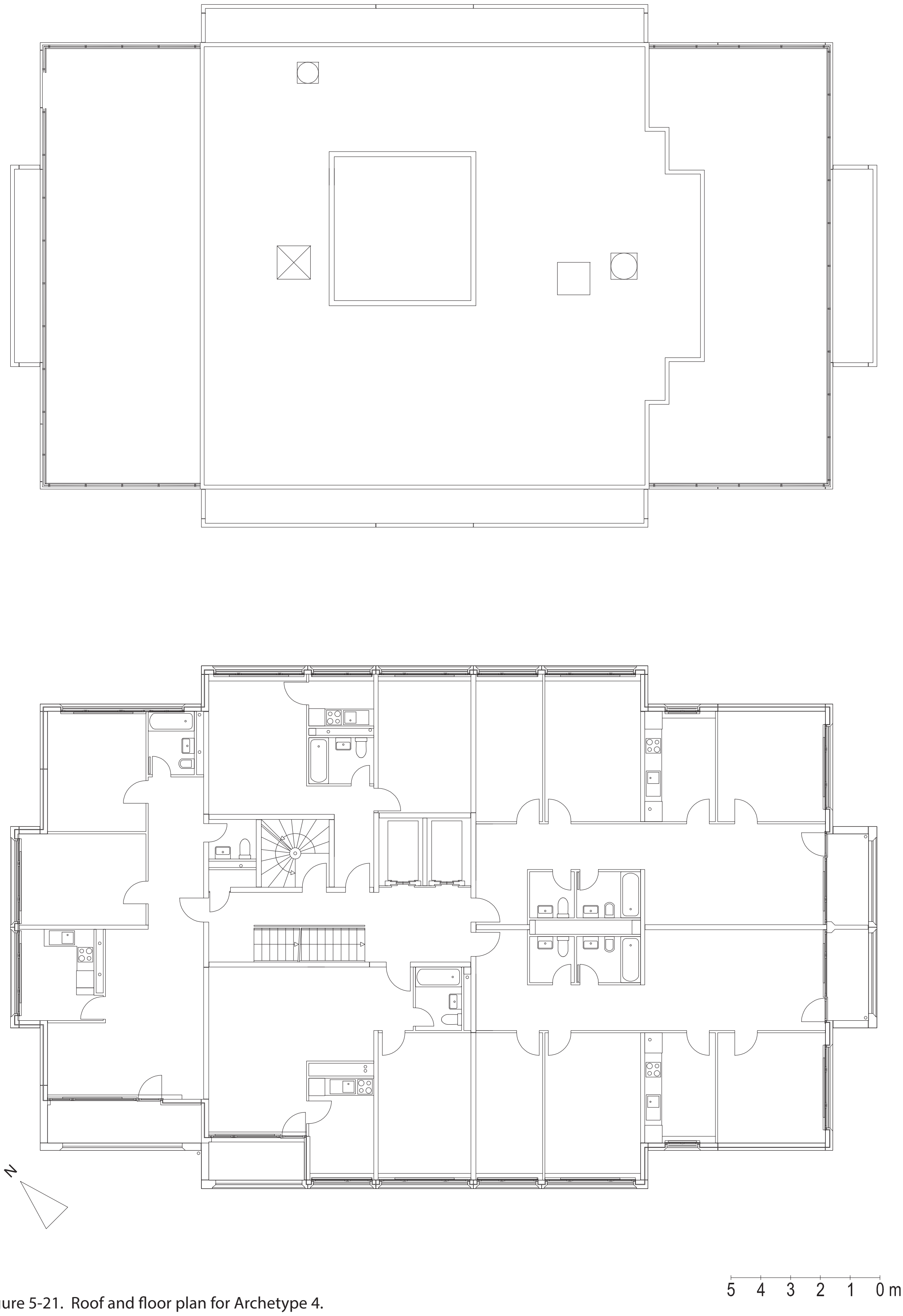


Figure 5-21. Roof and floor plan for Archetype 4.

Figure 5-22. Section for Archetype 4.

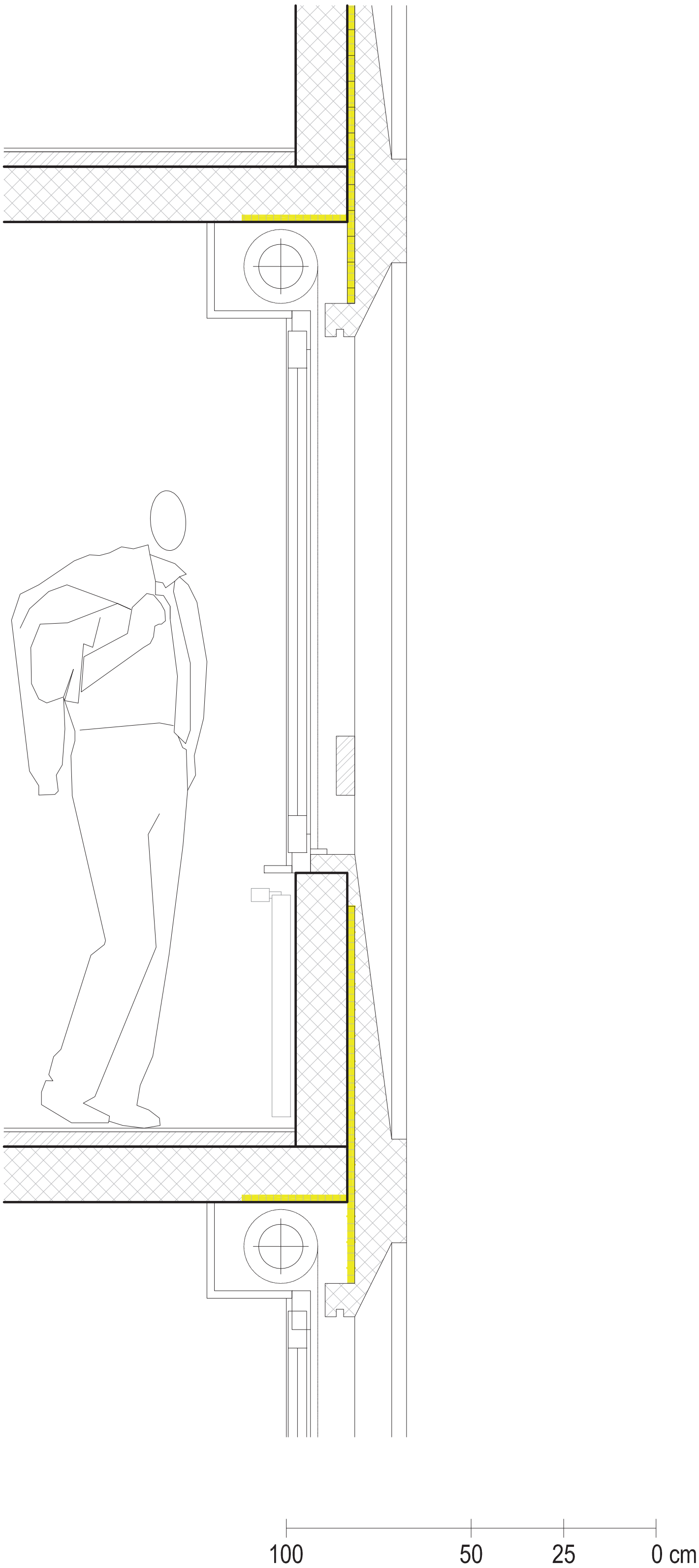


Figure 5-23. Façade and roof constructive detail, **E0 – Current Status**, Archetype 4.

Roof: Gravel 5 cm, Bitumen 0.2 cm, EPS expanded polystyrene (old) 6 cm, Cement screed 4 cm, Bitumen 0.4 cm, Reinforced concrete slab 22 cm, Gypsum plaster 1 cm.

Façade: Reinforced concrete 2-14 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 14 cm.

Internal floor (against non-heated space): Linoleum floor 0.5 cm, Cement screed 5 cm, Reinforced concrete slab 22 cm, Gypsum plaster 1 cm.

External floor (ground): Ceramic floor tiles 1 cm, Cement screed 6 cm, Reinforced concrete slab 22 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Reinforced concrete slab 22 cm.

Openings: Wooden frame windows with double-glazing 6-4(air)-6 mm.

Calibrated energy model

Building envelope characteristics

Table 5-8 shows a summary of the configuration values regarding the building envelope considering the constructive details for Archetype 4 (Figure 5-23), and a comparison of annual heating demand between the calibrated energy model simulation result and the energy bills provided by the owner for the years 2013, 2014 and 2015.

Archetype 4	U-Value	Energy model image
Roof*	0.62 W/m^2·K	
Façade*	0.98 W/m^2·K	
Internal floor*	2.19 W/m^2·K	
External Floor (ground)*	2.44 W/m^2·K	
Openings (glazing)**	2.90 W/m^2·K	
Infiltration rate	1.50 ACH	
Occupation rate	0.0380 m^2/person	
Annual energy demand comparison [kWh/ m^2·year]		
	Energy bill $_{(2013\text{-}2015)}$	Calibrated energy model
Heating demand (Oil)	78 kWh/ m^2·year	75.4 kWh/ m^2·year

Table 5-8. Summary of configuration data of the energy model and comparison between simulated and real heating demand for Archetype 4, scenario E0-Current status. Using data from: * Swiss construction catalogue [**Suisse Energie 2016**]; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder [**DesignBuilder 2018**]. Detailed information in Annexe 10.1.6.

Thermal bridges estimation

Table 5-9 shows the values adopted for each type of LTB, using reference values from the Swiss catalogue of thermal bridges **[Infomind Sàrl 2003]**.

Type	Linear thermal bridge (LTB) description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	1.3-I1	+0.68
TB2	Wall-Unheated ground floor	3.4-I1	+0.05
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.84
TB7	Blind box	4.2-A1	+0.26
TB8	Still below window	5.1-I2	+0.15
TB9	Jamb at window or door	5.2-I4	+0.14
TB10	Lintel above window or door	5.3-I1	+0.13

Table 5-9. Linear thermal bridges for Archetype 4 according to [**Infomind Sàrl 2003**]. Detailed information in Annexe 10.1.6.

5.3.5. Archetype 5

Description of case study building

Archetype 5, built in 1990, has an architectural expression and materials that situate it in its time / context, i.e. during the development of affordable residential neighbourhoods of the 1980's (Figure 5-24). This building is not protected; it is classified by the heritage department of Neuchâtel as Category III **[Neuchâtel 2005]**, i.e. disturbing building.

It is a 77-meter long bar, oriented north-south with a width of 13 meters, gable façades without openings and east and west façades with openings that allow the cross ventilation of the apartments. This 28-year old building shows few signs of deterioration.

The building responds to the slope of the ground, also north-south, with increasing living spaces depending on the height. The façade shows three bodies corresponding to the three platforms created to respond to the slope of the original terrain. It has four stories plus an attic under the curved roof (with slab and reinforced concrete beams) with 8 cm of insulation, and finished in copper sheet with exposed ribs each 60 cm. There are also two underground floors.

Two different organisations are observed at the level of the façades. Above floors 0 to 3 is a level of attic that is set back from the general façade plane, and whose expression is strongly detached from the rest of the building. Floors 0 to 3 have the same typology of flats with terrace-garden on the ground floor and semi-circular balconies on floors 1 and 2.

The 3rd floor and the attic are connected by a typology of duplex apartments, with the access located at the attic level through an outer corridor, covered by the continuation of the curved roof with the apparent concrete structure and metallic columns (round tubular profiles).

Façades are made of reinforced concrete (loading walls), with 12 cm of insulation, an air gap of 4 cm and an outer layer of yellow sand-limestone brick that gives it its final appearance. Green aluminium frames the double-glazed windows, with external aluminium blinds in the same colour as the windows. There is a gas boiler and a solar thermal system that covers about 50% of DHW needs.

Figure 5-24. Image of E0-Current status scenario, Archetype 5.

Main characteristics of the building (Figure 5-24 to Figure 5-28):

- Total floor area: 4’417 m^2 (Energy Reference Area – ERA: 3’453 m^2).
- Building from the period of development of affordable residential neighbourhoods (> 1980).
- Reinforced concrete load-bearing façade, 12 cm insulation, 4 cm void and outer layer of yellow silico-limestone brick (final appearance). Reinforced concrete slabs.
- Curved roof, insulated with 8 cm EPS, and entirely covered with a copper sheet.
- Double-glazed windows with green aluminium frame and external aluminium blinds.
- Gas boiler and solar thermal system covering about 50% of DHW requirements, located in front of the south gable façade using the reinforced concrete structure of an external staircase and the elevator.

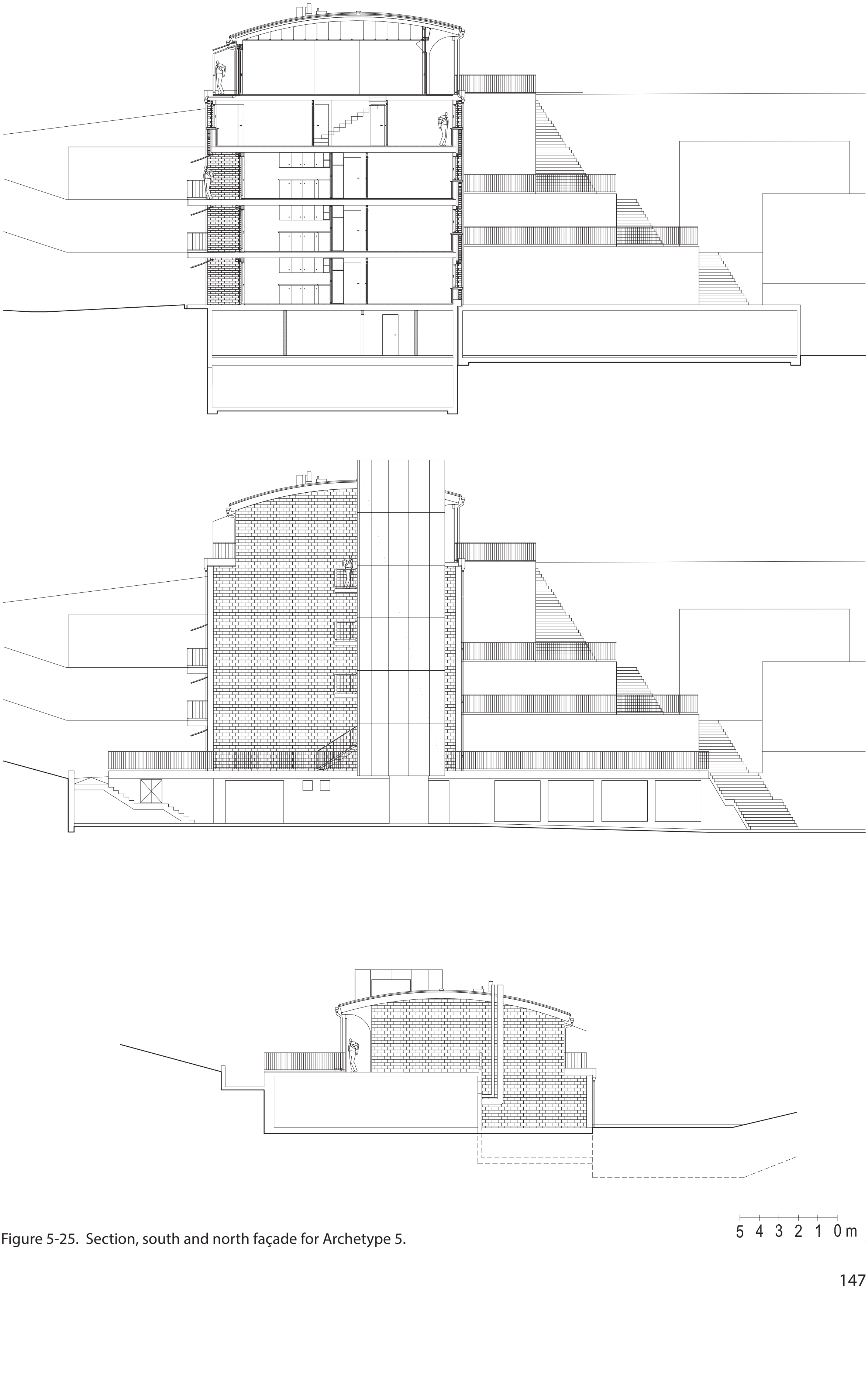


Figure 5-25. Section, south and north façade for Archetype 5.

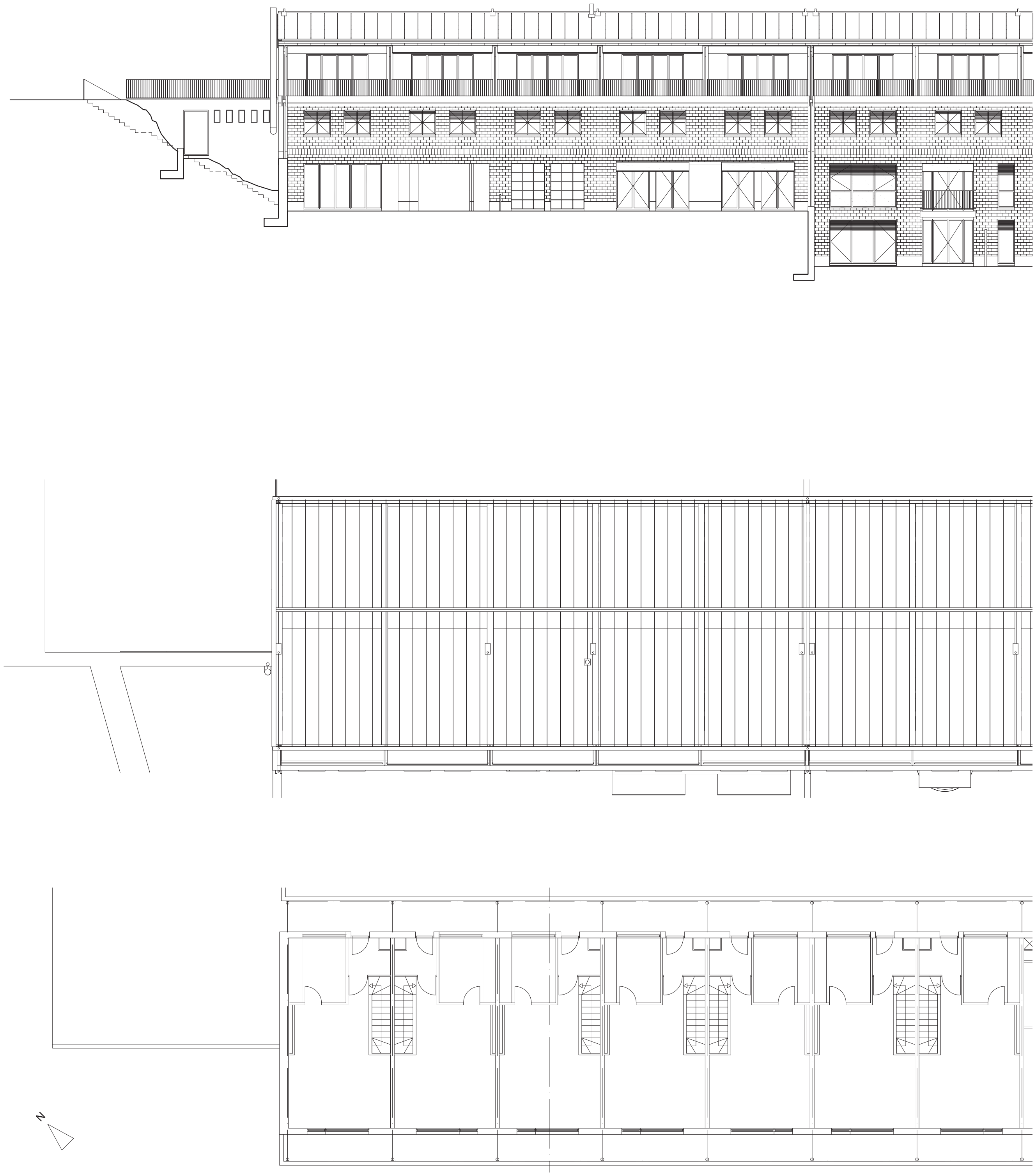
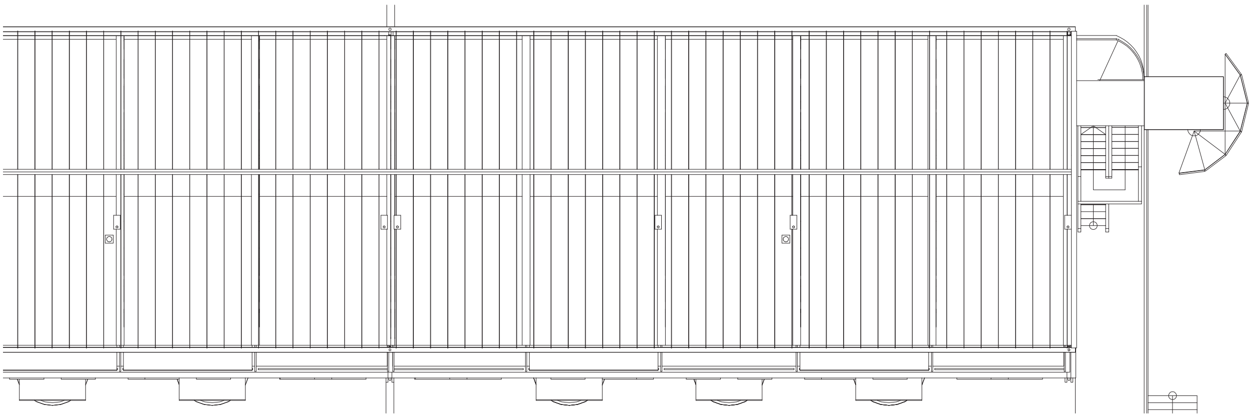
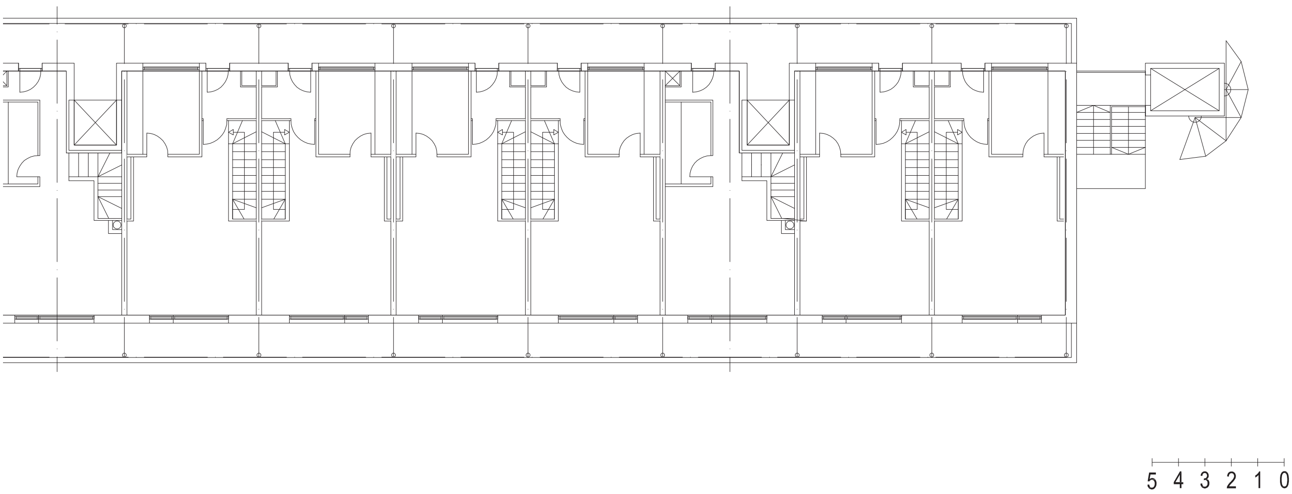


Figure 5-26. Façade, roof and 4th floor plan for Archetype 5.

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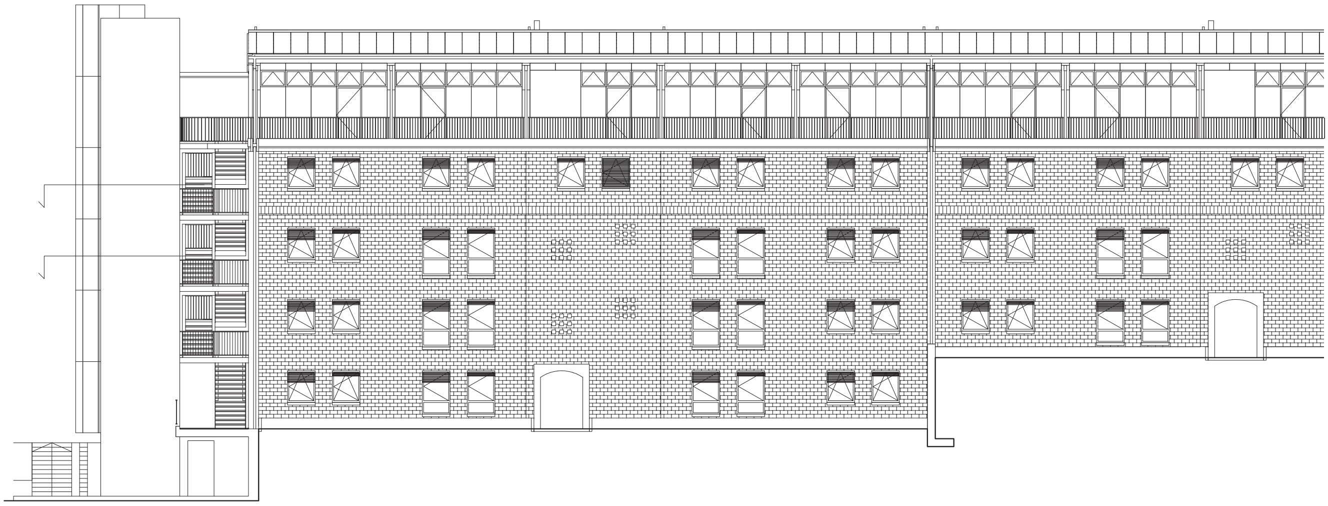
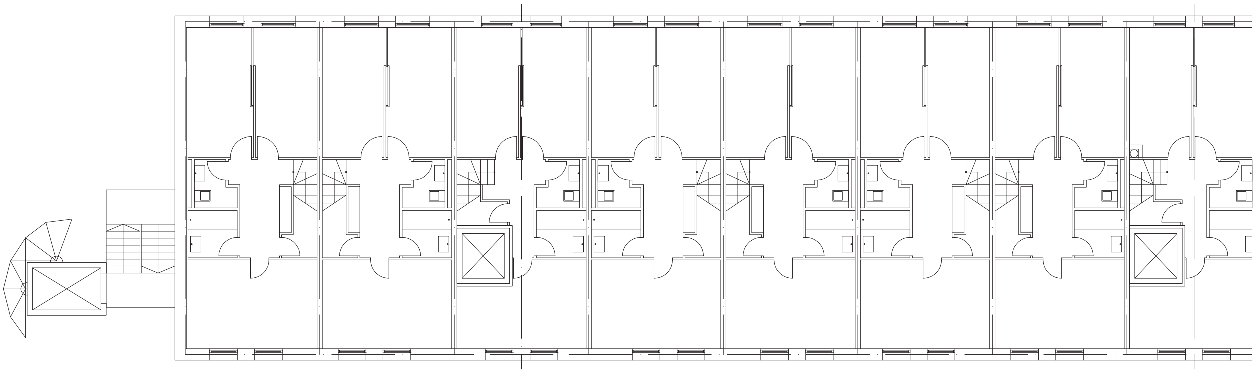




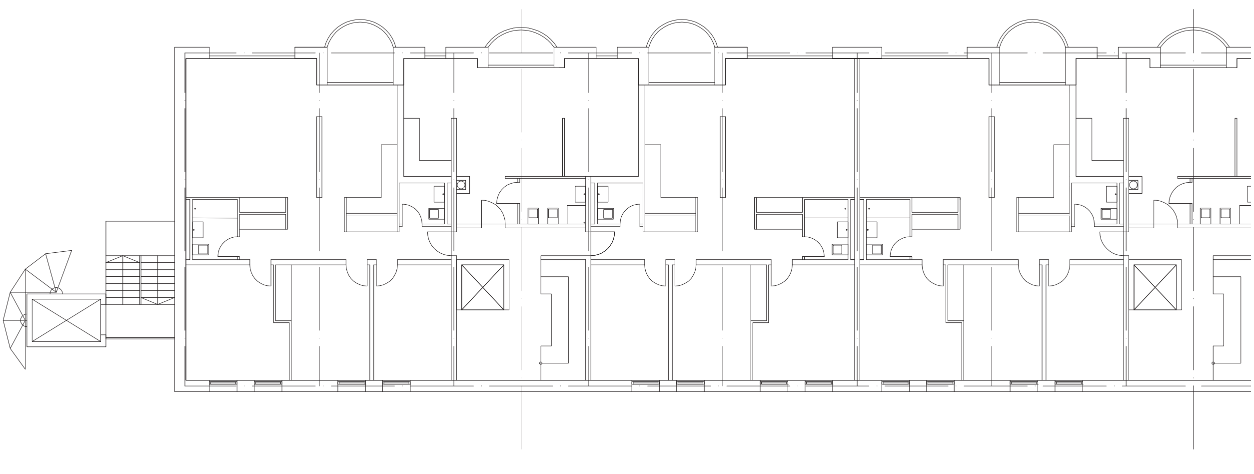
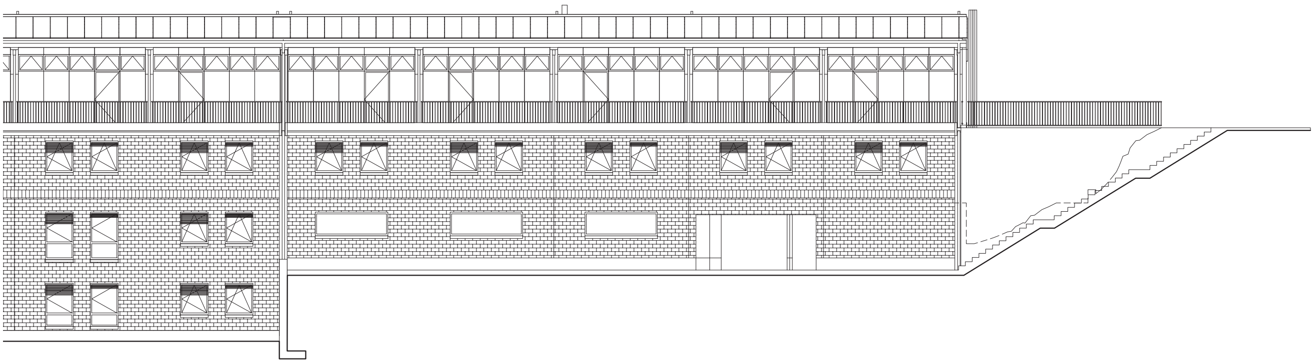
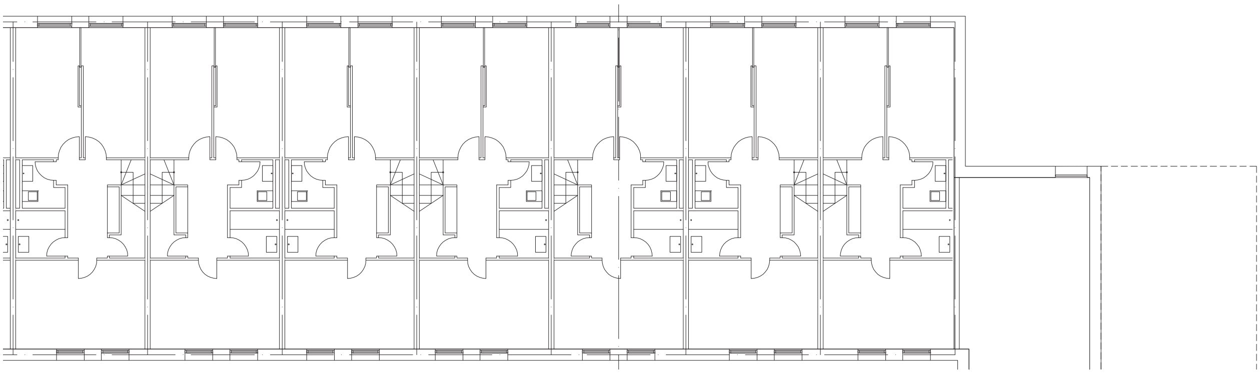
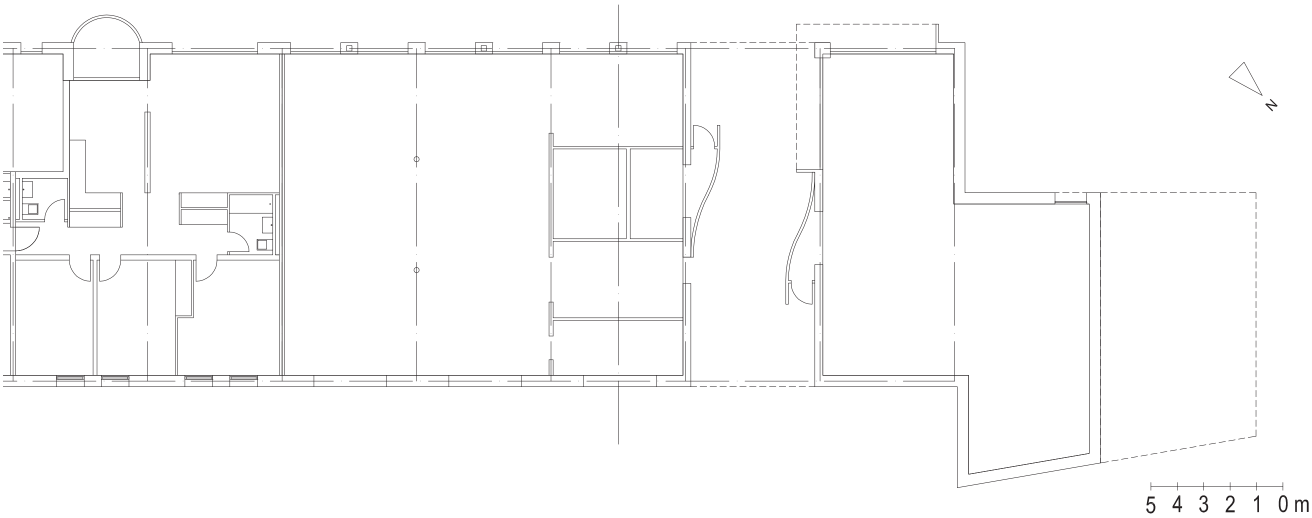


Figure 5-27. Façade, 3rd and 2nd floor plan for Archetype 5.



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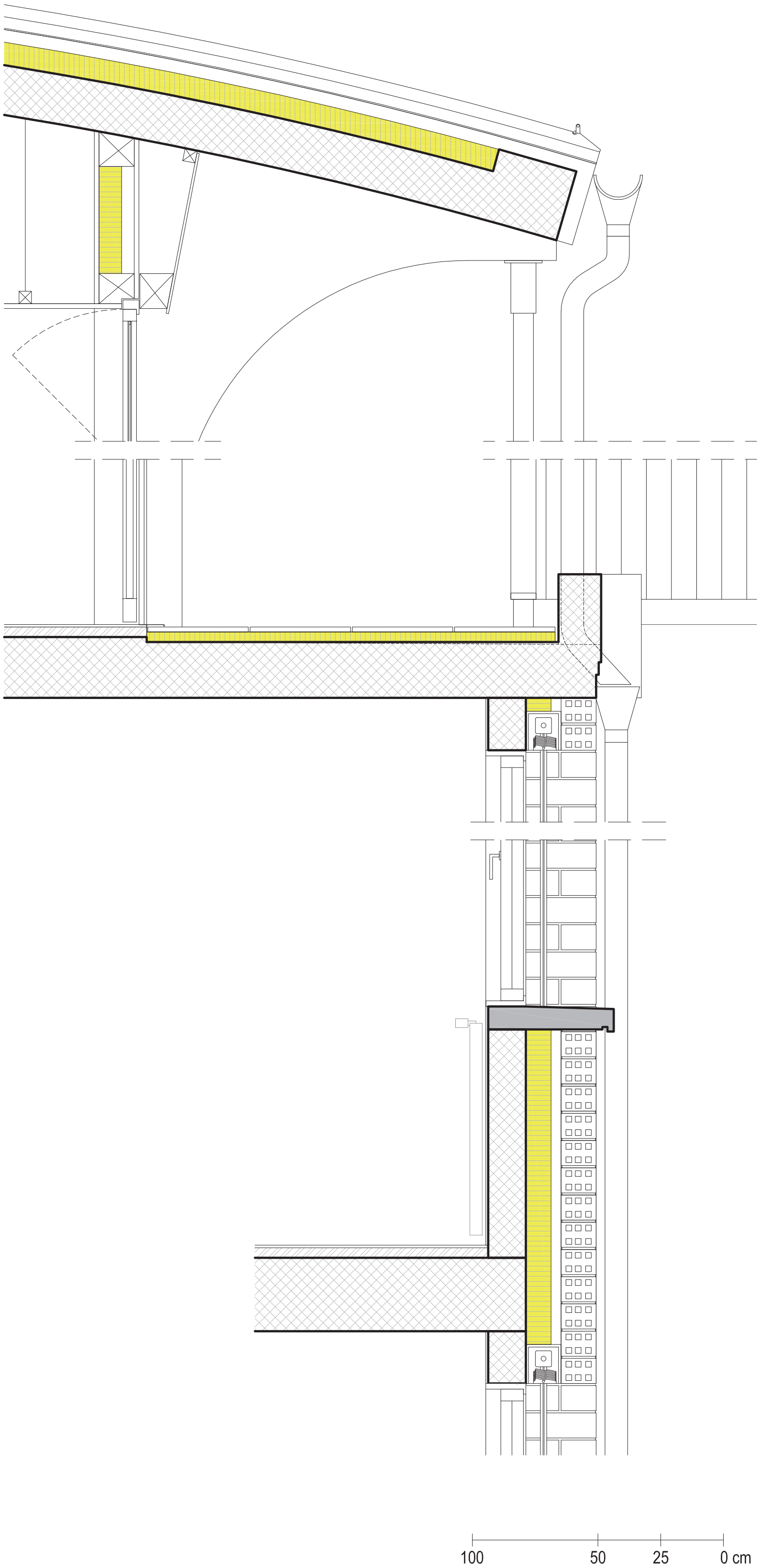


Figure 5-28. Façade and roof constructive detail, **E0 – Current Status,** Archetype 5.

Roof (curved): Zinc sheet 0.5 cm, Air gap 5 cm, EPS expanded polystyrene (old) 8 cm, Vapour barrier, Reinforced concrete slab 20 cm.

Roof (flat): Concrete tiles 2 cm, XPS extruded polystyrene 4 cm, Bitumen 0..4 cm, Reinforced concrete slab 22 cm.

Façade: Ceramic brick 14 cm, Air gap 4 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 15 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm.

External floor (ground): Ceramic floor tiles 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm.

Solar protections: Exterior aluminium blinds 10 cm.

Balconies: Reinforced concrete slab 30 cm.

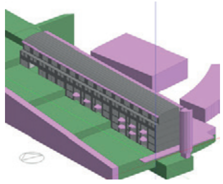
Openings: Aluminium frame windows with double-glazing 6+12(air)+6 mm.

Calibrated energy model

Building envelope characteristics

Table 5-10 shows a summary of the configuration values regarding the building envelope considering the constructive details for Archetype 5 (Figure 5-28), and a comparison of annual heating demand between the calibrated energy model simulation result and the energy bills provided by the owner for the period from 2009 to 2015.

Table 5-10. Summary of configuration data of the energy model and comparison between simulated and real heating demand for Archetype 5, scenario E0-Current status. Using data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.7.

<table>
<tr><th>Archetype 5</th><th>U-Value</th><th>Energy model image</th></tr>
<tr><td>Roof*</td><td>0.53 W/m²·K</td><td rowspan="7"></td></tr>
<tr><td>Façade*</td><td>0.59 W/m²·K</td></tr>
<tr><td>Internal floor*</td><td>1.78 W/m²·K</td></tr>
<tr><td>External Floor (ground)*</td><td>2.01 W/m²·K</td></tr>
<tr><td>Openings (glazing)**</td><td>2.98 W/m²·K</td></tr>
<tr><td>Infiltration rate</td><td>1.00 ACH</td></tr>
<tr><td>Occupation rate</td><td>0.0347 m²/person</td></tr>
<tr><td colspan="3">Annual energy demand comparison [kWh/ m²·year]</td></tr>
<tr><td></td><td>Energy bill (2009-2015)</td><td>Calibrated energy model</td></tr>
<tr><td>Heating demand (Gas)</td><td>64 kWh/ m²·year</td><td>68.5 kWh/ m²·year</td></tr>
</table>

Thermal bridges estimation

Table 5-11 shows the values adopted for each type of LTB, using reference values from the Swiss catalogue of thermal bridges **[Infomind Sàrl 2003]**.

Table 5-11. Linear thermal bridges for Archetype 5 according to **[Infomind Sàrl 2003]**. Detailed information in Annexe 10.1.7.

Type	Linear thermal bridge (LTB) description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	1.3-I1	+0.68
TB2	Wall-Unheated ground floor	3.4-I1	+0.05
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.84
TB7	Blind box	4.2-A1	+0.26
TB8	Still below window	5.1-I2	+0.15
TB9	Jamb at window or door	5.2-I4	+0.14
TB10	Lintel above window or door	5.3-I1	+0.13

5.4. Synthesis

This chapter has presented the five existing buildings selected to represent each of the five archetypes defined in Chapter 4. A detailed analysis of the buildings including their constructive details has served to determine the envelope's features and fully characterise the current status of the buildings, forming our scenario E0. From this information, 3D energy models were produced and calibrated using real energy consumption data obtained from owners' bills.

As can be seen from the photos shown of the buildings and from their characterisation, they are complimentary in terms of constructive features and architectural expression. These differences are essential to ensure a diverse coverage of the building stock through these selected archetypes, as well as to instigate a case-specific implementation of the renovation interventions and BIPV integrations in the next phase.

Differences are also reflected in the main values used to configure the thermal envelope in the energy model, summarised in Table 5-12. The U-values are systematically much higher than current regulation **[SIA 2016a]**, demonstrating the necessity of renovating the selected buildings.

The energy model obtained during this phase is used to implement renovation strategies and assess the design scenarios in terms of energy performance in the following phases presented in the next two chapters.

Archetype	**1**	**2**	**3**	**4**	**5**
	U-Value [W/m²·K]				
Roof*	1.59	0.93	0.91	0.62	0.53
Façade*	1.07	1.13	1.18	0.98	0.59
Internal floor*	0.94	1.06	1.06	2.19	1.78
External Floor (ground)*	1.74	1.63	0.60	2.44	2.01
Openings (glazing)**	5.70			2.90	2.98
	Infiltration rate [ACH]				
Airtightness	2.00			1.00	1.00

Table 5-12. Summary of configuration data of the energy model for the five archetypes in scenario E0-Current status. Using data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.

6. Development of design scenarios

This chapter describes Phase 3 of the methodology, as well as its application on the five real case studies and the final results through architectural visualisations (computer-generated images). The objective is here to propose a series of renovation scenarios with BIPV integration to then carry out a multi-criteria evaluation (Chapter 7).

Before describing in Section 6.2 the three BIPV scenarios (S1-Conservation, S2-Renovation, and S3-Transformation), two scenarios used as reference for comparative purposes are presented in Section 6.1. These correspond to the E0-Current status scenario, already described in Chapter 5, and the S0-Baseline scenario, which reflects common renovation practice. These two scenarios will serve to comparatively show the improvement potential of each BIPV scenario proposed. The S0-Baseline scenario will particularly allow to highlight the advantages offered by the integration of photovoltaic energy within the building renovation process.

Section 6.3 describes the process for implementing the scenarios on each archetype, which is done in Section 6.4., where results are notably shown through computer-generated images.

6.1. Reference scenarios

6.1.1. Current status

The first reference scenario, E0-Current status presented in the previous chapter, allows detecting all BIPV Integration opportunities in the thermal envelope for each building. From that study, knowledge is also gathered regarding the demands of the built environment (e.g. in terms of neighbour buildings colours, textures, proportions, heritages protections), to which will have to respond the scenarios' application for each archetypal situation to ensure the integration of the design within the existing urban context.

6.1.2. Current practice

After the study of the current status, a S0-Baseline scenario is defined, with the aim to achieve at least the current legal requirements defined by SIA 380/1:2016 **[SIA 2016a]**, in terms of annual heating demand (Qhli for renovation projects, see formula in Annexe 10.2). This scenario is defined through a conservative approach, in accordance with current practices, without taking into account BIPV strategies and only implementing passive strategies to reduce the energy demand (by improving the performance of the envelope using low-cost or the most affordable materials).

This scenario thus allows highlighting what the improvement potential is using the most commonly applied strategies as in professional practice, prioritising the most affordable strategies to reach only the minimum legal requirements.

6.2. BIPV design scenarios

As mentioned in **[Peters et al. 2018]** (p.1), *"Architects design for the future. The act of drawing is a predictive act of experimenting with possible futures. The buildings architects design today form the cities of the future. Necessary optimists, architects design to archive better ways of living – turning 'existing situations into preferred ones' [Herbert Alexander 1996]. […] Simulation is a way in which designs can be tested for their future performance."*

Following this line of thought, the idea is here to position ourselves in a prospective situation in which an architecture office is confronted to a client who wants to renovate their building. In this hypothetical situation (where the demands for buildings that preserve the environment are increasing and ceasing to be optional), architects should be able to propose refurbishment strategies integrating solar power, specifically BIPV elements.

Thus, the objective is to provide material to support architects in doing so, through detailed definitions of the application of BIPV scenarios on case studies, using the most commonly used tools by architects (e.g. plans, sections, 3D visualisations and renderings). In that way, we will show how BIPV can be integrated into the design process of the different renewal scenarios, according to different levels of intervention described below.

6.2.1. Architectural design scenarios and strategies

This section describes the objectives of each BIPV design scenario, from an architectural design perspective, and by framing each scenario within the energy efficiency and environmental objectives according to the requirements of the 2050 targets. The main strategies put in place are first introduced below.

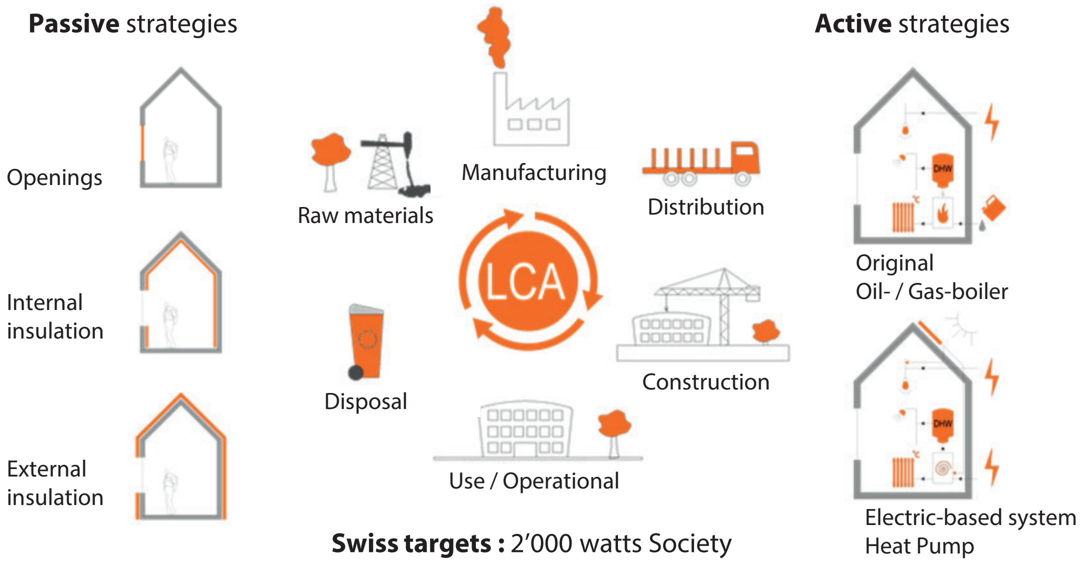


Figure 6-1. Life-Cycle Analysis (LCA) approach to define scenario strategies.

To explore the implementation of BIPV scenarios with different levels of intervention allowing to obtain a range of possible solutions and confront them to the 2050 targets, scenarios are developed by implementing: 1) Passive strategies (also used for S0), to improve the envelope through low-embodied energy materials and construction systems; 2) BIPV strategies, using innovative photovoltaic products as a new material for façades and roofs; and 3) Active strategies, adapting HVAC systems to improve the efficiency of the BIPV installation and reducing the dependence on the feed-in-tariffs to ensure the profitability of investments. For this, a Life-Cycle Analysis (LCA) approach is followed as shown in Figure 6-1.

The chosen nomenclature for the three BIPV scenarios gives an idea of what is intended with each scenario:

S1-Conservation: This scenario aims to maintain the substance / expression of the building when possible (considering current practice), while improving its energy performance by replacing defective elements with more performing ones (e.g. windows, wall internal insulation), to reach at least the current legal requirements defined by SIA 380/1:2016 standard **[SIA 2016a]**. In addition, unlike the S0-Baseline scenario (current practice), from this scenario onwards we propose to respect the targets enabling to obtain a subsidy of 60 CHF/m^2 from the *"programme bâtiment"* **[EnDK 2018b]**, which promotes energy renovation of existing buildings' envelope.

S2-Renovation: This scenario corresponds to maintaining the general expressive lines of the building while reaching high energy performance (deep retrofit including placing PV elements wherever possible). This scenario offers the possibility of exploring the limits of a mimicry approach, trying to imitate the materiality of the existing building using active (BIPV) elements. In terms of energy performance objectives, we consider as reference at least the requirements fixed by the Swiss Minergie® label **[Minergie 2018]**.

S3-Transformation: This final scenario proposes a global strategy corresponding to maximising the photovoltaic contribution towards reaching the best energy performance possible with aesthetic and formal coherence of the whole building, but by allowing the image of the building to be changed in a more obvious way, in order to achieve at least the objectives of the 2'000-Watt Society **[SIA 2017a]** according to the Energy strategy 2050 **[OFEN 2018a]**. The results of this scenario should show the energy performance improvement potential for each type of building and the feasibility of achieving the 2'000-Watt Society concept targets. This scenario prioritises the use of prefabricated elements with low-impact materials (e.g. wood, recycled EPS insulation) as proposed by **[Zimmermann 2012]**.

In combination with the integration of BIPV in S1 to S3, an additional active strategy is implemented, consisting in the replacement of the original HVAC system – oil- (**OIL**) or gas-boiler (**GAS**) – by an electricity-based system (**HP**) to increase the self-consumption of the electricity produced on-site and reduce the consumption thanks to high-efficiency air-water heat-pumps (Coefficient Of Performance, COP, of 2.8). This also allows reducing the environmental impact linked to the type of energy source used for heating and domestic hot water (DHW) demand.

6.2.2. Design criteria to apply BIPV design scenarios

The general design concepts presented in the previous section are to be implemented considering the specific characteristics of each building. Consequently, the strategies are adapted to each case study to provide the most adequate means for achieving the design objectives.

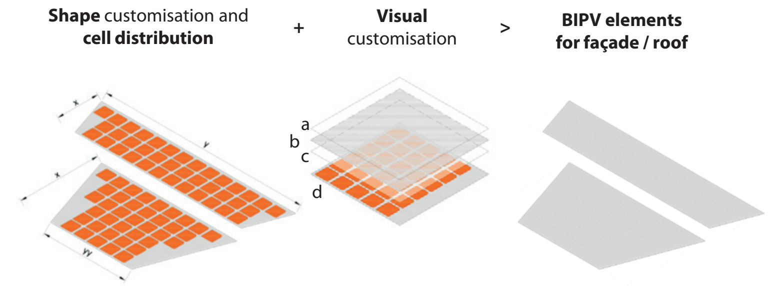
The integration of BIPV products is done using mainly the opaque available surfaces – including roof and façades – with flat BIPV panels (considering both standard and customised elements) based on the well-known and mature crystalline silicon (c-Si) technology. This allows bypassing some barriers related to the uncertainty over the durability and performance of cutting-edge products like perovskite **[CCEM 2012a]** (see also Chapter 3, Section 3.2.3).

Moreover, the most flexible products in terms of size (e.g. the MegaSlate® series of PV panels from 3S Solar Plus company [**3S Solar Plus AG 2018**]) are used. However, with the aim of projecting this research into the future, we also make use of new and emerging low-cost customisation techniques mainly developed by CSEM (e.g. Solar-Terra **[ISSOL 2018]**, Solaxess [**Solaxess 2018**]) **[Escarré et al. 2015]** and based on standard c-Si cells PV panels as a support material.

The advantage of using mature technologies with glass-glass **[Peike et al. 2013]** configuration (for the front and rear cover of the PV modules) is the guarantee that these BIPV products are in accordance with the directive of products for construction (89/106/EEC), which means that they can be used as envelope material. For example, modules commercialised by ISSOL are designed according to EN-12543, EN-572-5, EN-12150-1 standards (tempered safety glass), to IEC-61215, IEC-61730 (solar glass standards), to EN-13823 and EN-13501-1 standards (fire resistance), to EN-12600 standard (pendulum impact test), and CE marked.

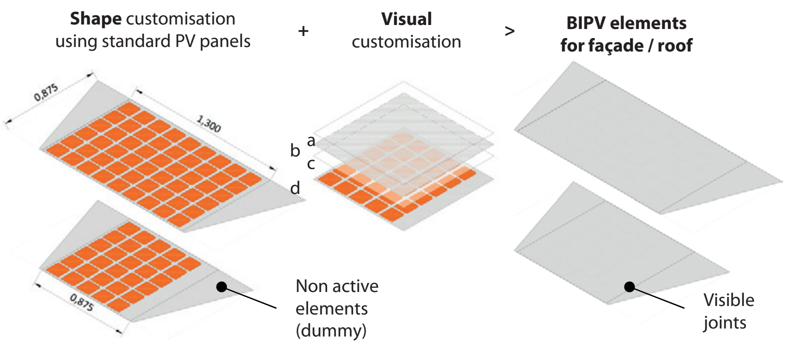
Some criteria are defined to implement these design scenarios on a case study:

- The general approach should be from an integration point of view, constructively but also in the sense of integrating the BIPV strategies in the general energy concept of the building (e.g. acting on the HVAC system to make it more compatible with the new consumption reality of the building).
- Whenever possible, prioritise the substitution of an inert or non-active construction element by active BIPV element, to showcase examples of BIPV integration, reducing the use of non-integrated (BAPV) approaches.
- Use a mature technology (c-Si PV cells) in order to avoid some uncertainties (performance estimation, prices and warrantied lifespan).
- Use existing and new low-cost customisation techniques.
- Prioritise *"standard-size"* modules considering the maximum size recommended for manufacturing performance reasons (3.8x2.4m) and the prescription of the custom-made execution of the manufacturer (freedom in terms of cells disposition within the PV module).
- To illustrate what can be done with existing products, in a first design iteration, adapt – depending on the design objectives of the scenario – the design of the façade / roof to the product specifications, according to Figure 6-2 and Figure 6-3 for scenarios S1 and S2, and according to Figure 6-4 (larger and more standard panels) for the more futuristic S3 scenario.



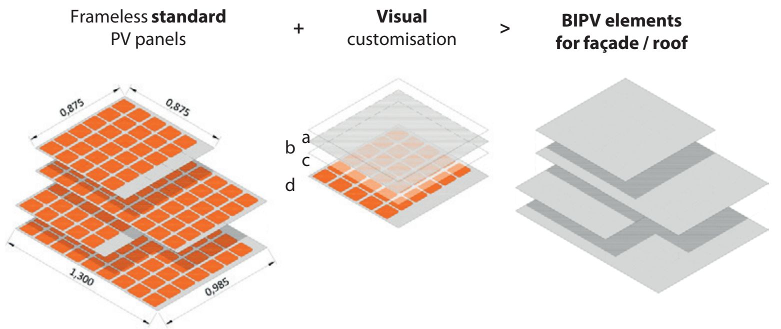
(a) Front encapsulation
(b) Reflecting **coloured film** [highly reflects visible light while transmitting infrared]
(c) Back encapsulation
(d) Standard frameless PV panel

Figure 6-2. Technological approach for S1-Conservation design scenario implementation.



(a) Front encapsulation
(b) Reflecting **coloured film** [highly reflects visible light while transmitting infrared]
(c) Back encapsulation
(d) Standard frameless PV panel

Figure 6-3. Technological approach for S2-Renovation design scenario implementation.



(a) Front encapsulation
(b) Reflecting **coloured film** [highly reflects visible light while transmitting infrared]
(c) Back encapsulation
(d) Standard frameless PV panel

Figure 6-4. Technological approach for S3-Transformation design scenario implementation.

The technological approach for the application of the **S1-Conservation** scenario consists in considering the possibility to prioritise the use of customised BIPV elements, both in terms of shape and visual aspect (using a coloured film during the encapsulation process) (Figure 6-2). In that way, active elements can be integrated in specific zones where a relatively complex geometry must be respected, without changing the aspect of the building. This allows to avoid having visible joints that may hinder the reproduction of the desired architectural design.

For the application of the **S2-Renovation** scenario, low-cost customisation techniques are used to adapt the appearance of standard-sized c-Si PV panels through the introduction of coloured film during the encapsulation process of the panels (Figure 6-3). Although relatively cheap, this customisation method implies accepting some visible joints between the standard panel's parts and the non-active elements. These non-active elements (also called dummies) are custom-made with the necessary shape to be adapted to the geometry of the building and have the same appearance as the active elements.

For the application of the **S3-Transformation** scenario, the design of the façade / roof is adapted in function of standard-size and -shape BIPV panels that are only customised visually (with the same type of coloured film than the other approaches), if required by the design (Figure 6-4). In addition, this approach leaves the possibility to use larger panels reflecting the manufacturing flexibility – thanks to the synergies between solar and glass industry – that is emerging as mentioned in Chapter 3. Through this scenario, practically new façades emerge, to maximise the possible active surfaces by maintaining a formal coherence of the aspect of the building. For example, a prefabricated ventilated façade, modulated according to standard-size panels, enables reaching an almost 100% active façade. This prefabricated façade is in fact proposed for many of the archetypes, as seen in Section 6.4, not only due to the above PV-integration reasons, but also given the benefits (e.g. lower environmental impact and cost) and growing interest for such industrialised products as highlighted in Chapter 3 (Section 3.1.1).

As mentioned, the objective of this last technological approach is to go as far as possible in terms of energy performance to evaluate what is the maximum potential of each type of building. In addition, this approach also aims to show what can currently be done in terms of design, to highlight that even in this intermediate stage of technological development, it is possible to make a quality architecture that respects the 2050 targets.

The adaptation of the architectural design to the available products should be considered as a transitional step in the process of expanding BIPV technology to large-scale renovation projects, since in principle – the obligation to modulate a façade according to the dimensions of standard products – is something that architects would not be willing to do by default. Yet, this thesis aims to promote the use of this BIPV technology to dislodge the current trend of the sector. Projecting towards the future, as soon as the demand for BIPV products that can be adapted to the design requirements increases, the development of this market should be enhanced with evermore products with greater flexibility / adaptability.

6.2.3. Comparative energy-use scenarios

In addition to the three architectural design renovation scenarios described above, three comparative energy-use scenarios regarding the BIPV sizing are investigated. Introduced below, these are further described in Chapter 7, Section 7.2.3.

A-100%: using all possible active surfaces identified from this phase (shown in Section 6.4). These surfaces are defined in order to respect the design intention behind each scenario (S1-S3) and are divided according to the sizes of the PV panels considered for each scenario and archetype.

B-Selection: adjusting the number and location of active surfaces to the energy needs of the building by conducting a selection process based on finding an equilibrium (or trade-off) between self-sufficiency (SS) and self-consumption (SC), by filtering the active surfaces using an annual irradiation threshold (this active surface selection method is fully described in Chapter 7, Section 7.2.4).

C-Batteries: in addition to adjusting the active surfaces (B-Selection), implementing an energy storage system based on ion-lithium stationary batteries.

Moreover, two different approaches are explored to see how the energy is going to be used: 1) **Injection** (Feed-in Tariff; FiT), giving the possibility to inject the energy overproduced (that cannot be self-consumed) into the grid in exchange of a revenue per kWh, and a 2) **No injection** (Self-Consumption; SC) approach, where only the self-consumed energy is taken into account in the energy balance, showing the results if the possibility of injection into the grid was not available.

6.3. Scenarios implementation workflow

This section describes the steps in Phase 3 of the global workflow, shown in Figure 6-5, regarding the implementation of the renovation design scenarios described in the previous sections.

Starting with **Step 4**, all graphical data are generated to show the implementation of each design scenario (S0, S1, S2 and S3). In **Step 5a**, the different renovation strategies are implemented into an energy model for each scenario. This energy model is based on the calibrated model of E0-Current status obtained from **Phase 2**. For S0, the insulation is increased for all opaque surfaces and windows are replaced to respectively reach the U-value target of 0.25 $W/m^2{\cdot}K$ and 1.30 $W/m^2{\cdot}K$ set by the SIA 380/1:2016 requirements [**SIA 2016b**]. For scenarios S1, S2 and S3, the target is to achieve a U-value of at least 0.19 $W/m^2{\cdot}K$, required to obtain subsidies from the *"Programme Bâtiment"* [**EnDK 2018b**].

Step 5b consists in checking if the minimum energy performance target of the SIA 380/1 [**SIA 2016a**] is achieved for each scenario in terms of heating energy demand. The calculation of this minimum requirement (Qhli,re) is detailed in Annexe 10.2 and values are shown in Figure 6-71 of Section 6.5 along with the obtained demand for each scenario (Qh). This iterative process, carried out through energy simulations in the DesignBuilder v.5 software [**DesignBuilder 2018**], allows adjusting the energy models (e.g. further refining the passive measures).

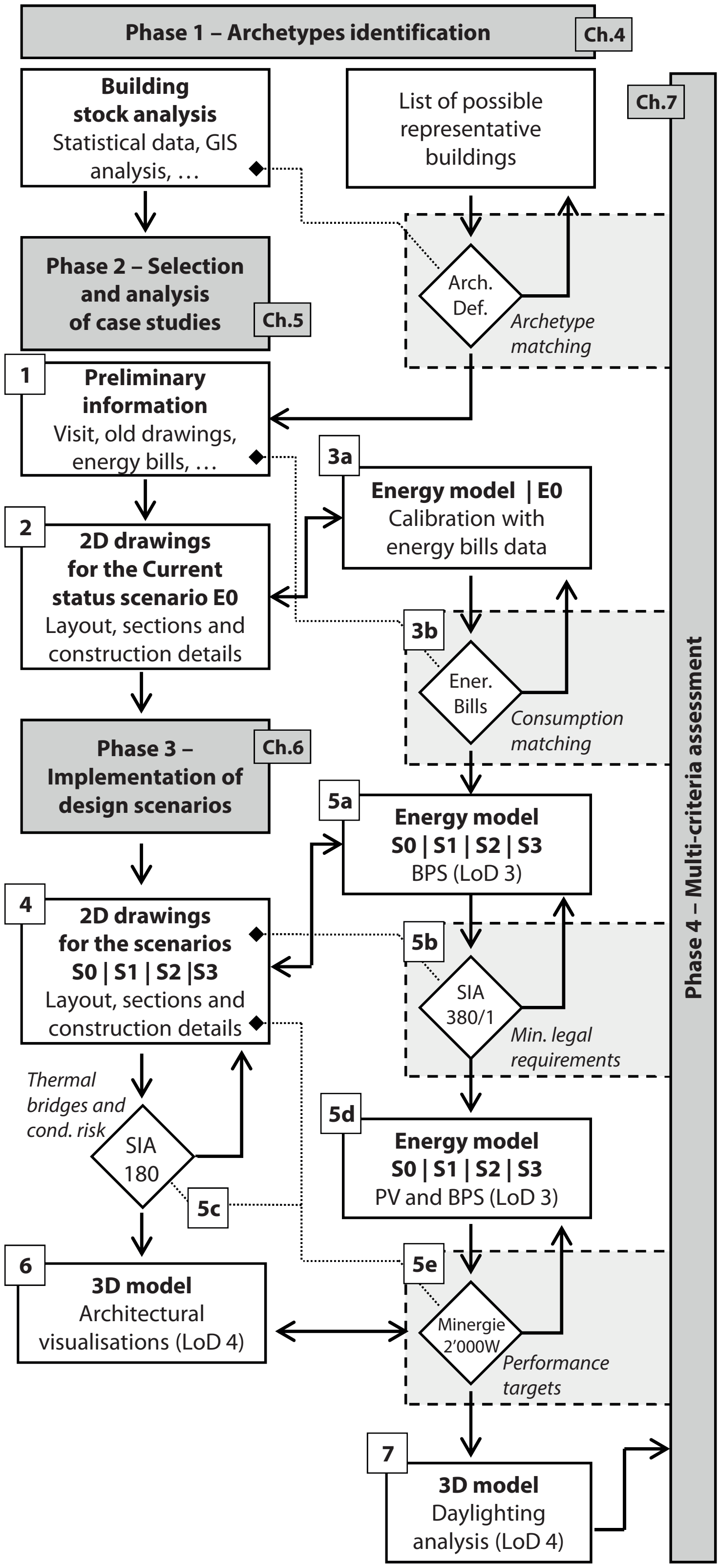


Figure 6-5. Global workflow illustrating the links between Phase 3 and the other Phases 1, 2 and 4

In **Step 5c**, the viability of the most important details in terms of thermal bridges, condensation and mould formation risk are verified according to the standard SIA 180:2014 **[SIA 2014]**. This standard defines the thermal bridge analysis method in order to evaluate the risk of condensation and mould on surfaces and prevent excessive moisture in building elements by diffusion and capillarity. Indeed, apart from the loss of energy through linear thermal bridges (LTB; also called cold bridges), another consequence of LTB is the low indoor surface temperature that causes water vapour contained in the interior air to condense, in turn producing mould. Although most published studies about renovation projects do not take into account thermal bridges in the simulations since, as highlighted by [**Branco et al. 2002**], they lack in-depth analysis at the construction level, controlling for humidity problems is important, especially when adding interior insulation [**CCEM 2008; Stahl et al. 2012; PAP 2013**]. Given that conducting a detailed thermal bridge study is complex and time-consuming, catalogues of standard values can be used, such as [**Infomind Sàrl 2003**]. In **Step 5d**, once the constructive details and the potentially active surfaces are defined, a detailed model is generated to study the production of photovoltaic energy in relation to the energy demand of the building, as well as to simulated the different comparative energy-use scenarios regarding the BIPV sizing (A-100%, B-Selection, C-Batteries) considering the two different energy balance approaches (with/without injection into the grid).

Step 5e consists in a validation process comparing the results to the energy performance targets defined for each design scenario. All requirements (SIA 380/1:2016, Minergie® label and 2'000-Watt Society) are already described in Chapter 3, Section 3.1.3. Figure 6-72 in Section 6.5 illustrate this verification for the Minergie® standard. From the final design thus obtained, the hourly consumption of the building during the entire year for each renewal scenario is simulated, allowing to conduct the final multi-criteria evaluation, presented in **Phase 4** (Chapter 7). In addition, a high level of detail (LoD 4) model is generated in order to produce a computer-generated image of the design scenario implementation (**Step 6**) and to check the impact of the renovation strategies on the daylighting potential (**Step 7**).

In relation to the modelling and simulation of the different renewal proposals, the level of detail (LoD) used to generate the various 3D models is crucial to guarantee the accuracy of the assessment. The CityGML standard defines 4 levels of details from LoD 1 to LoD 4 (Table 6-1), depending on the amount of available information about the building [**Gröger et al. 2007a**]. According to the objectives of this research, for the needs of PV calculation at building scale, a LoD 3 model would be the best option for architectural models, as it provides all the necessary details about wall and roof structures, balconies, bays and projections. A detailed context including terrain and the other buildings is also included to take into account solar obstructions. However, as suggested in previous studies [**Compagnon 2004; Carneiro 2011; Catita et al. 2014; Perez 2014; Fath et al. 2015**], for daylighting calculation the LoD 4 is needed, adding the interior structures, interior walls, doors, stairs and furniture to the LoD 3 model.

With all data obtained from this phase, three energy models for each design scenario are built: (1) **DesignBuilder** model for global energy performance of the building (energy demand and consumption) at LoD 3, (2) **Rhino** model for irradiation and photovoltaic analysis at LoD 3, and (3) **Rhino** model for daylighting potential analysis at LoD 4. These models are built and modified in parallel to the implementation of the different renovation scenarios. Table 6-2 shows an example corresponding to Archetype 1.

	Model scale description	Classes of accuracy (3D points distance)	Building installations	Roof overhanging parts
LoD 1	City, region	Low (5x5m)	-	-
LoD 2	City districts, projects	Medium (2x2m)	-	-
LoD 3	Architectural models (outside), landmark	High (0.5x0.5m)	Representative exterior effects	Simplified
LoD 4	Architectural models (interiors)	Very high (0.2x0.2m)	Real object form	Detailed

Table 6-1. Level of Detail according to the CityGML standard (adapted from **[Gröger et al. 2007b]**).

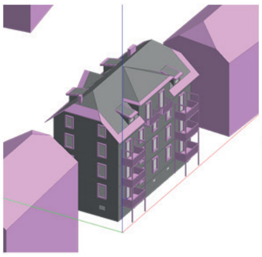
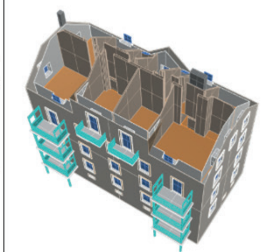
1) Energy performance	2) Photovoltaic analysis	3) Daylighting
		
LoD 3		LoD 4

Table 6-2. Example of different 3D models for Archetype 1, scenario S3-Transformation.

6.4. Implementation on case studies

The sub-sections below illustrate and describe the application of the design scenarios (S0-S3) on each case study (archetype), presenting:

- The implementation measures for S0 to S3, with visualisations (drawings and computer-generated images) of the outcomes over the main façade and roof and of the constructive details. As a general approach for S0 representing current practice, the insulation is increased for all opaque surfaces and windows are replaced. For S1 to S3, in addition to the interventions of S0, BIPV elements are integrated on roof and façades considering the requirements of each design scenario, and more ecological materials are favoured (e.g. wooden window frames) over low-cost materials (e.g. PVC window frames) particularly for the S3 scenario.
- Illustrations of the position of the potentially active surfaces after the renovation design implementation on the building envelope for S1-S3. These surfaces will serve for applying (in Chapter 7) the three comparative energy-use scenarios (A-100%, B-Selection and C-Batteries) in terms of BIPV sizing introduced in Section 6.2.3.
- Table presenting the final U-value of the different parts of the building envelope for each design scenario. Details on the different layers that compose each part of the envelope as well as the characteristics of the materials considered can be found in Annexe 10.1.
- Table of the main LTB values, estimated (through calculation) or selected (using default values from a Swiss catalogue **[Infomind Sàrl 2003]**), used to configure the energy model of each scenario. The full calculation method and detailed condensation / mould risk checking analyses are in Annexe 10.1.
- Compliance verification between the energy simulation results and the performance objectives set for each scenario regarding 1) the minimum legal requirements (SIA 380/1:2016), and 2) the compliance with the different Swiss Minergie® standard labels and the 2'000-Watt society targets.

6.4.1. Archetype 1

S0-Baseline | Archetype 1

Figure 6-6. Computer-generated image of scenario S0-Baseline, Archetype 1.

For the **S0-Baseline** scenario of this archetype (Figure 6-6, Figure 6-7 and Figure 6-8), the strategies adopted correspond to:

- External thermal insulation composite system (ETICS).
- Replacement of existing windows and shutters.

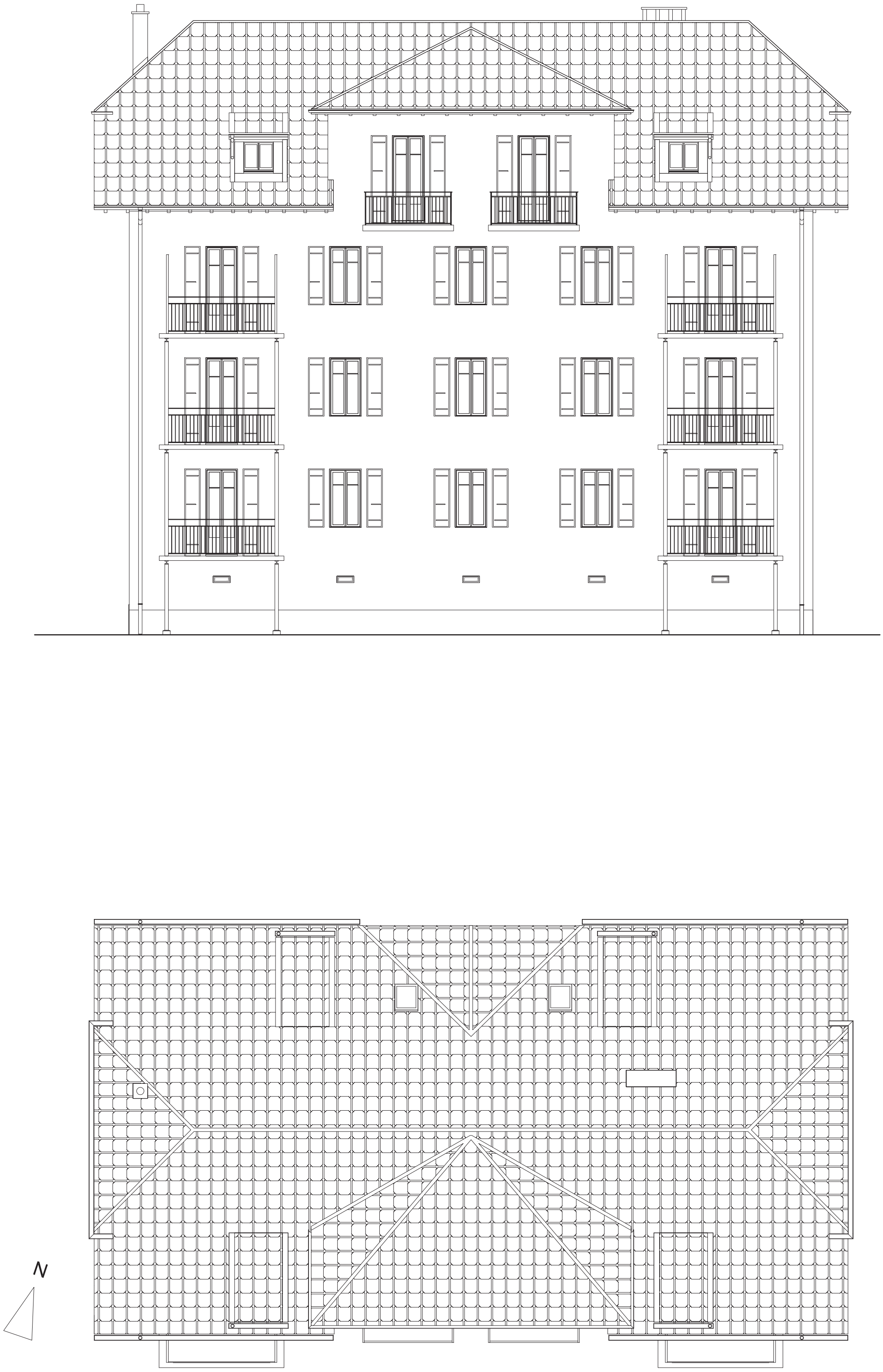


Figure 6-7. Design scenario S0-Baseline, Archetype 1.

5 4 3 2 1 0 m

Figure 6-8. Façade constructive detail, **S0 - Baseline**, Archetype 1.

Roof: Tiles and slats 8 cm, Hardboard 0.6 cm, Oak lathing 5 cm, Mineral wool insulation 12 cm, Vapour barrier, Solid wood 1.5 cm.

Façade: Synthetic plaster / reinforced mesh 1 cm, XPS extruded polystyrene 12 cm, Exterior plaster 2 cm, Rubble masonry 40 cm, Gypsum plaster 1cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement mortar 3 cm, Hallow slab / concrete 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

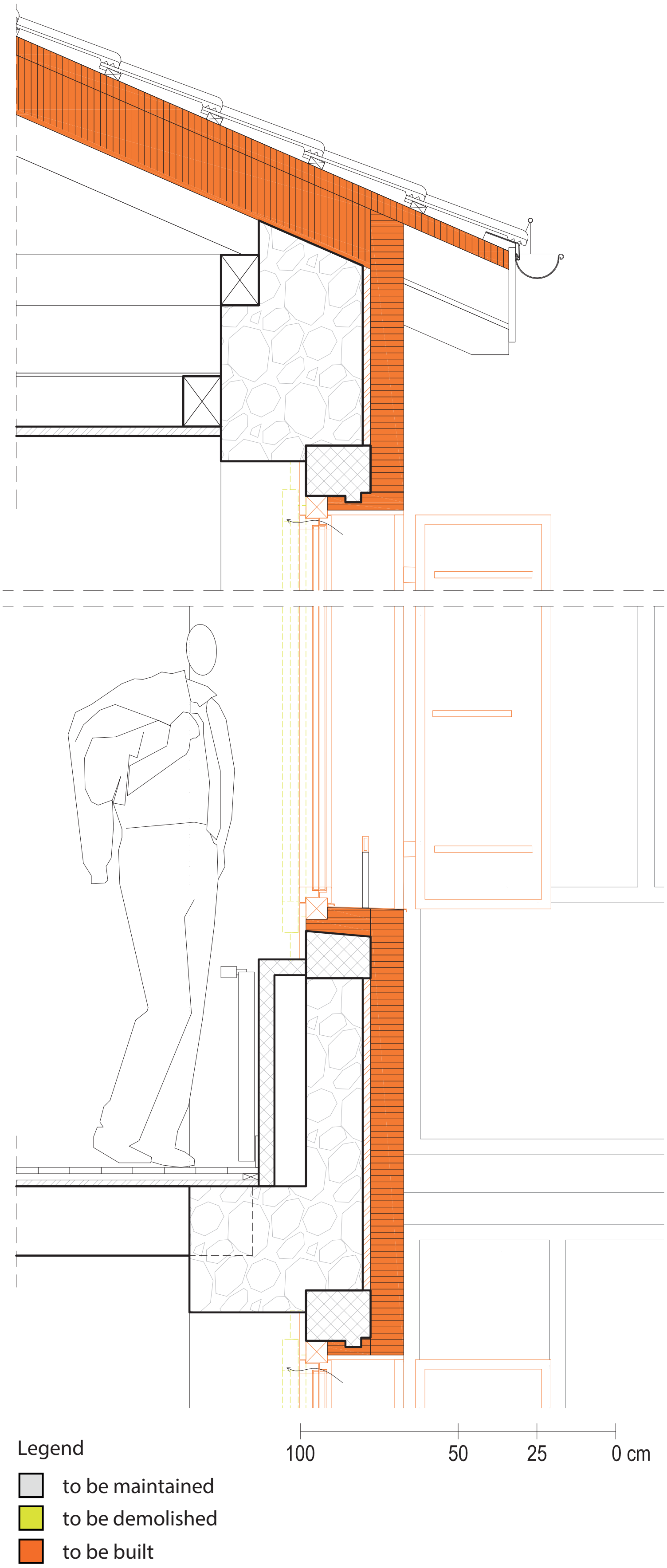
External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cast concrete slab 20 cm.

Solar protections: Wooden shutter 3cm.

Balconies (replaced): Cement slabs 12 cm, Metallic profiles IPE 100.

Openings: PVC frame windows with double-glazing 4-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)



S1-Conservation | Archetype 1

Figure 6-9. Computer-generated image of scenario S1-Conservation, Archetype 1.

For the **S1–BIPV conservation** scenario (Figure 6-9, Figure 6-10 and Figure 6-11), in addition to the interventions of S0-Baseline, we propose to cover the roof using standard-size coloured BIPV elements, in order to maintain the building's expression. The added intervention corresponds to:

- BIPV elements on the roof (190 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Standard size according to MegaSlate® system with dummies elements to complete roof coverage.
  - Visual customisation using Terracotta coloured film.
  - Final performance estimation of about 14.5% in STC.

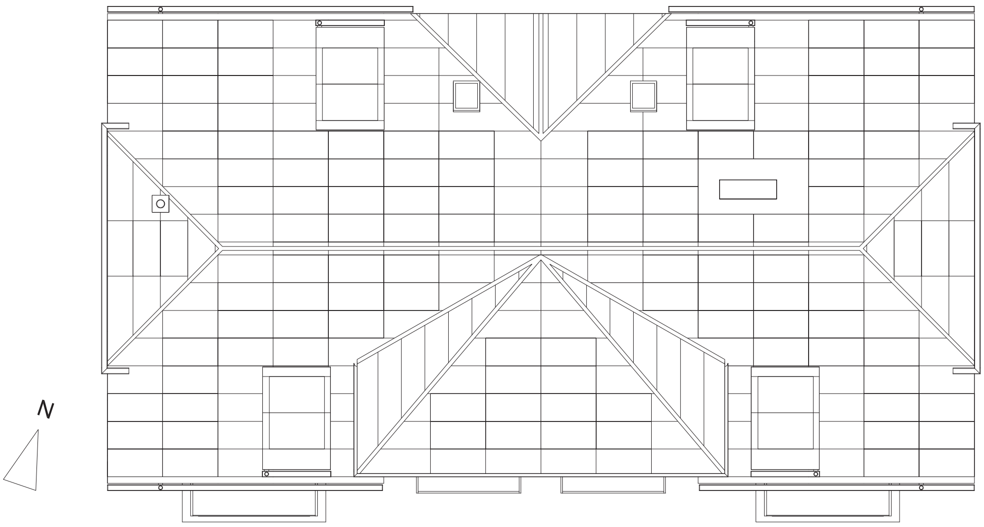


Figure 6-10. Design scenario S1-Conservation, Archetype 1.

5 4 3 2 1 0 m

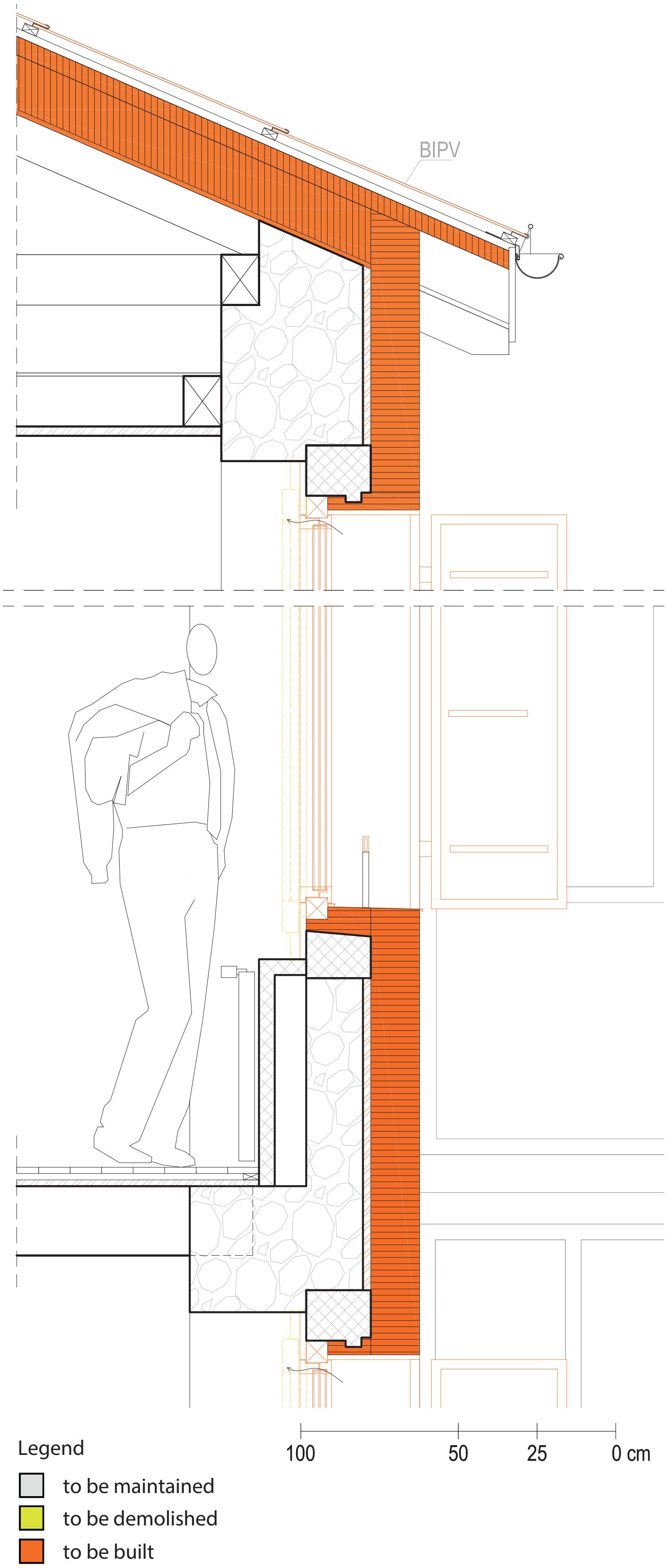


Figure 6-11. Façade constructive detail, **S1-Conservation,** Archetype 1.

Roof: Standard-size PV panels, Terracotta coloured film with η-14.5% (STC), Hardboard 0.6 cm, Oak lathing 5 cm, Mineral wool insulation 16 cm, Vapour barrier, Solid wood 1.5 cm.

Façade: Synthetic plaster / reinforced mesh 1 cm, XPS extruded polystyrene 14 cm, Exterior plaster 2 cm, Rubble masonry 40 cm, Gypsum plaster 1cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement mortar 3 cm, Hallow slab / concrete 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cast concrete slab 20 cm.

Solar protections: Wooden shutter 3 cm.

Balconies (replaced): Cement slabs 12 cm, Metallic profiles IPE 100.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S2-Renovation | Archetype 1

Figure 6-12. Computer-generated image of scenario S2-Renovation, Archetype 1.

For the **S2–BIPV renovation** scenario (Figure 6-12, Figure 6-13 and Figure 6-14), the above interventions are implemented (S0, S1) and coloured BIPV panels are installed on balcony railings, maintaining the main lines of the building's expression. The additional strategy is:

- BIPV elements on the balconies (19 m^2):
  - Frameless PV panels with mono-Si cells technology.
  - Size customisation, adapted to the existing balconies.
  - Visual customisation using mate blue coloured film.
  - Final performance estimation of about 13.5% in STC.

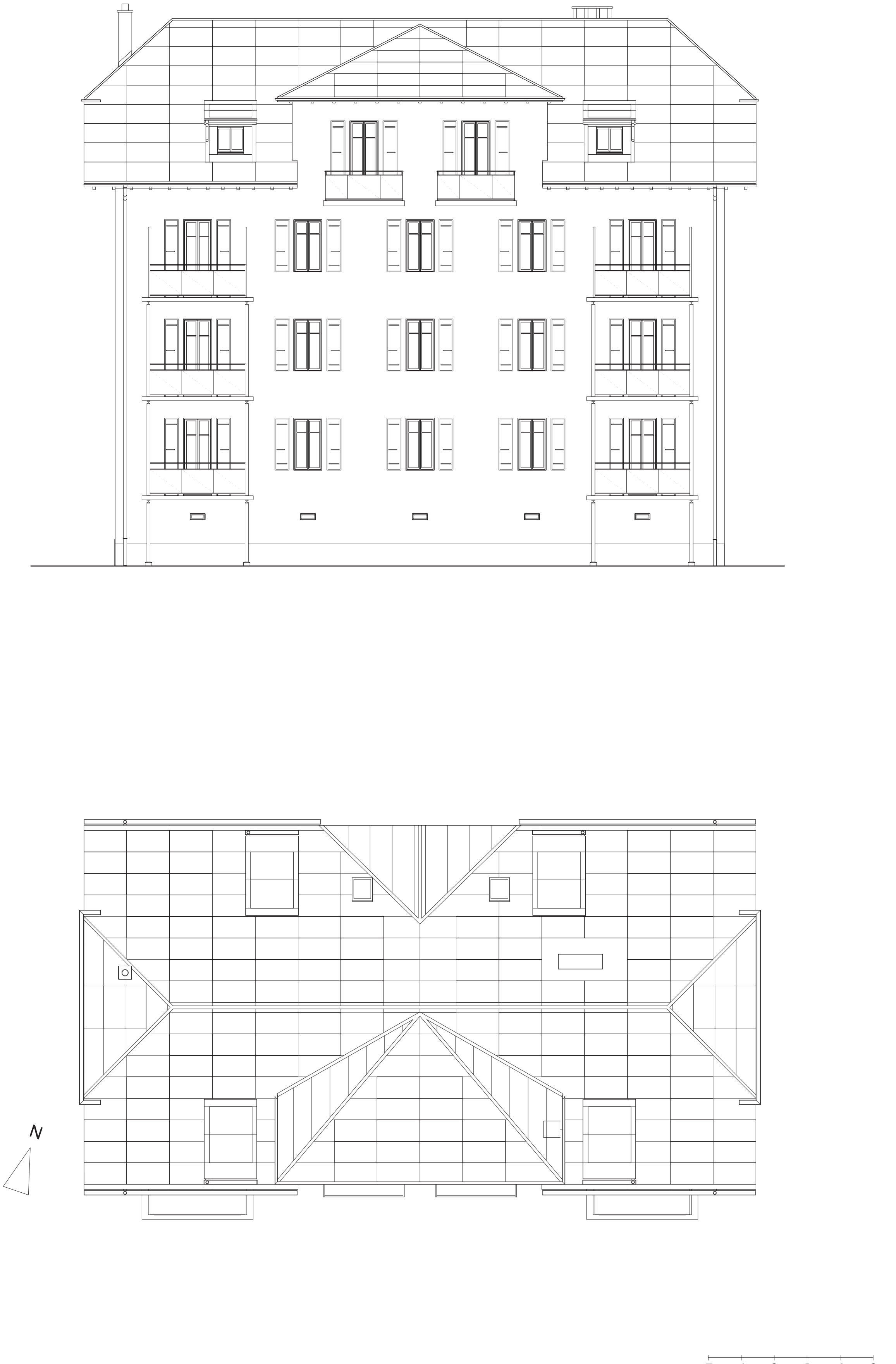


Figure 6-13. Design scenario S2-Renovation, Archetype 1.

Figure 6-14. Façade constructive detail, **S2 – BIPV Renovation**, Archetype 1.

Roof: Standard-size PV panels, Terracotta coloured film with η-14.5% (STC), Hardboard 0.6 cm, Oak lathing 5 cm, Mineral wool insulation 18 cm, Vapour barrier, Solid wood 1.5 cm.

Façade: Synthetic plaster / reinforced mesh 1 cm, XPS extruded polystyrene 16 cm, Exterior plaster 2 cm, Rubble masonry 40 cm, Gypsum plaster 1cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement mortar 3 cm, Hallow slab / concrete 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

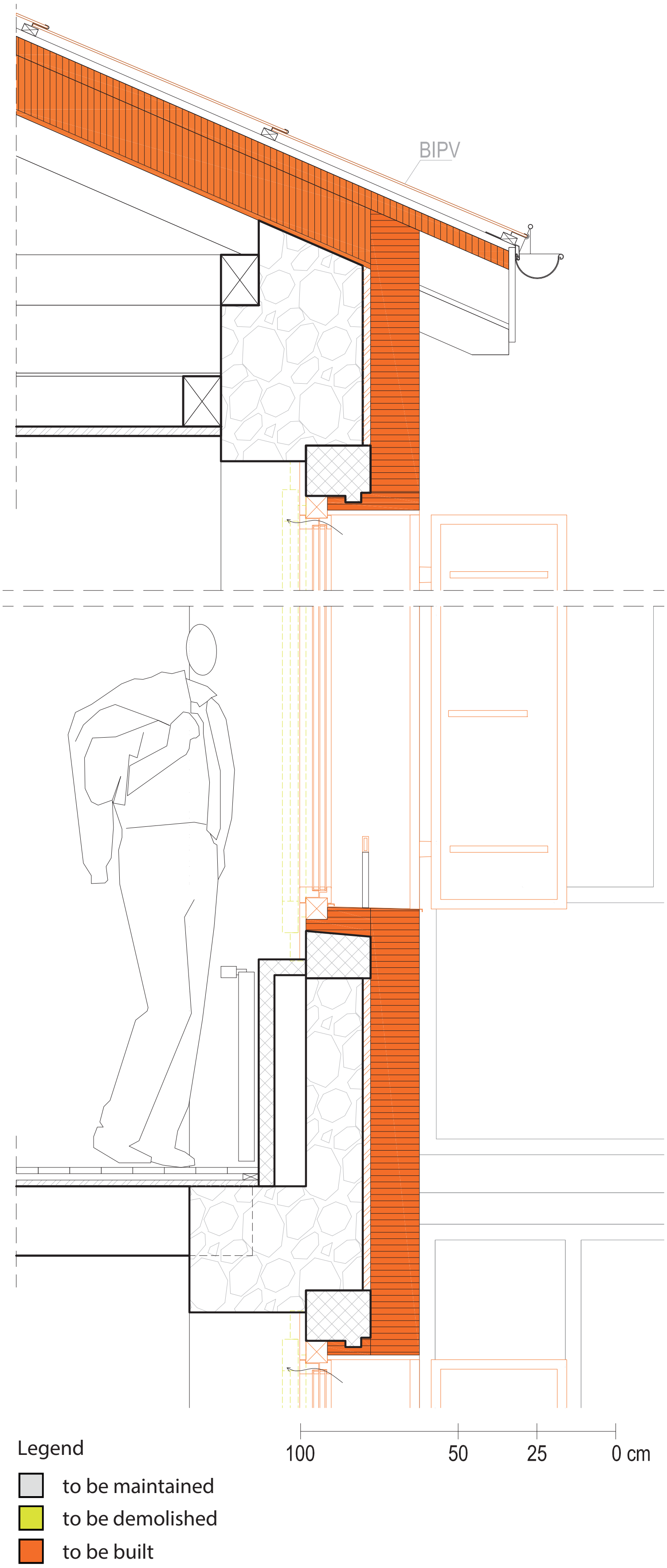
External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cast concrete slab 20 cm.

Solar protections: Wooden shutter 3 cm.

Balconies (replaced): Custom-size PV panels, Matt blue coloured film with η-13.5% (STC). Cement slabs 12 cm, Metallic profiles IPE 100.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)



S3-Transformation | Archetype 1

Figure 6-15. Computer-generated image of scenario S3-Transformation, Archetype 1.

Finally, for the **S3–BIPV transformation** scenario (Figure 6-15, Figure 6-16 and Figure 6-17), we propose a prefabricated wooden structure façade to plug-in directly on the existing façade, including external insulation (ventilated façade), new windows and BIPV elements covering all opaque surfaces. The strategies adopted correspond to:

- Timber frame prefabricated ventilated façade system, prioritising low-carbon materials, including all the envelope components and modulated according to the standard size of BIPV elements. Existing balconies are replaced by a new standalone structure reducing the thermal bridge with the façade.

- BIPV elements on the roof (190 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Standard size according to Megaslate® system with dummies elements to complete roof coverage.
  - Visual customisation using Terracotta coloured film.
  - Final performance estimation of about 14.5% in STC.
- BIPV elements in façade (378 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3’800 mm, width 50-2’400 mm) using 6” standard size solar cells **[metsolar 2018a]** and minimising the variety of dimensions to simplify the electric connections.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.
- BIPV elements on the balconies (25 m^2):
  - Frameless PV panels with mono-Si cells technology.
  - Size customisation, adapted to the new balconies.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.

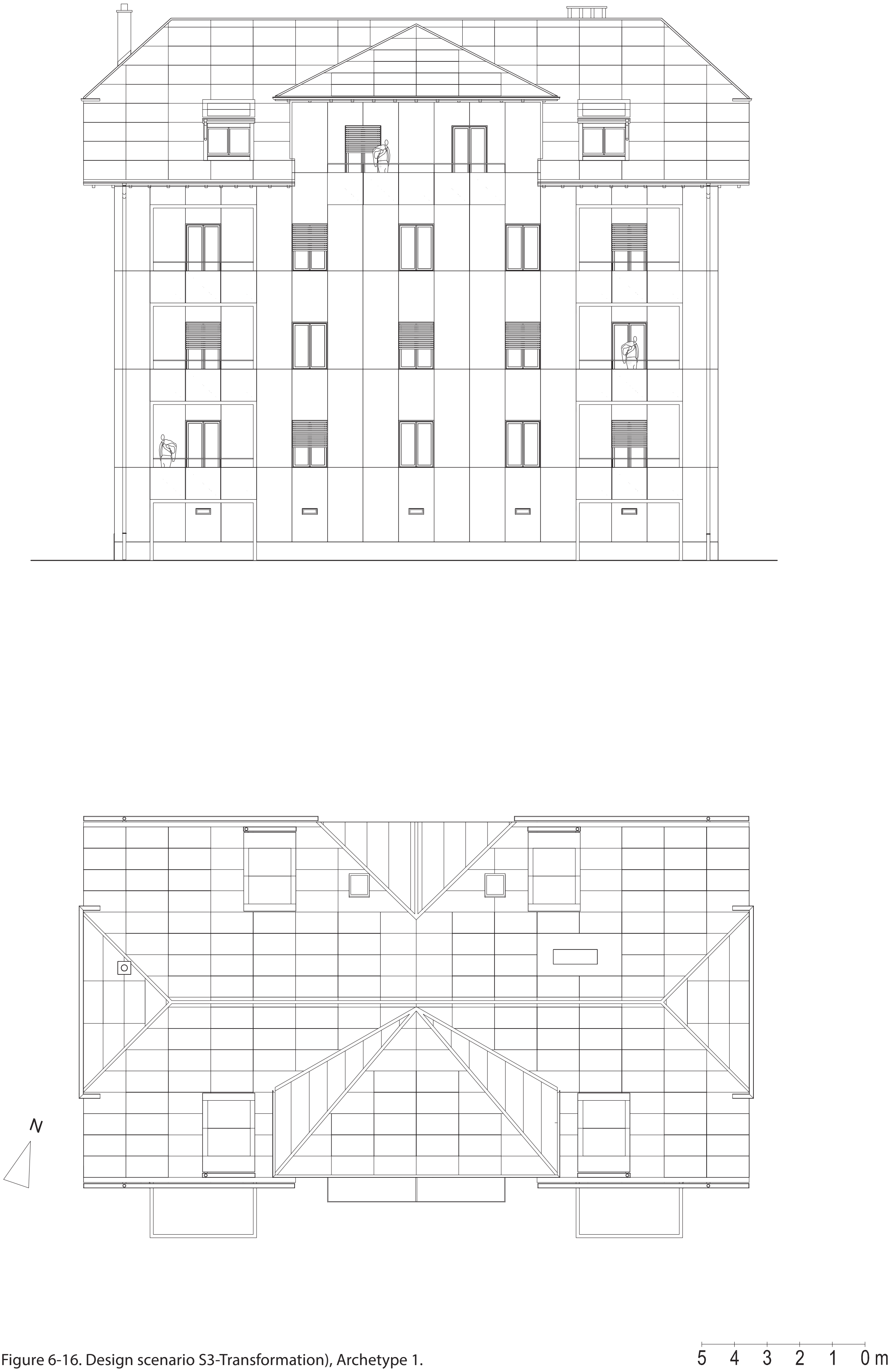


Figure 6-16. Design scenario S3-Transformation), Archetype 1.

Figure 6-17. Façade constructive detail, **S3 – BIPV Transformation**, Archetype 1.

Roof: Standard-size PV panels, Terracotta coloured film with η-14.5% (STC), Hardboard 0.6 cm, Oak lathing 5 cm, Mineral wool insulation 18 cm, Vapour barrier, Solid wood 1.5 cm.

Façade: Custom-size PV panels, Light grey coloured film with η-11% (STC), Air gap 5 cm, Wood particle board 1.5 cm, EPS expanded polystyrene (100% recycled) 18 cm, Wood particle board 1.5 cm, Exterior plaster 2 cm, Rubble masonry 40 cm, Gypsum plaster 1cm.

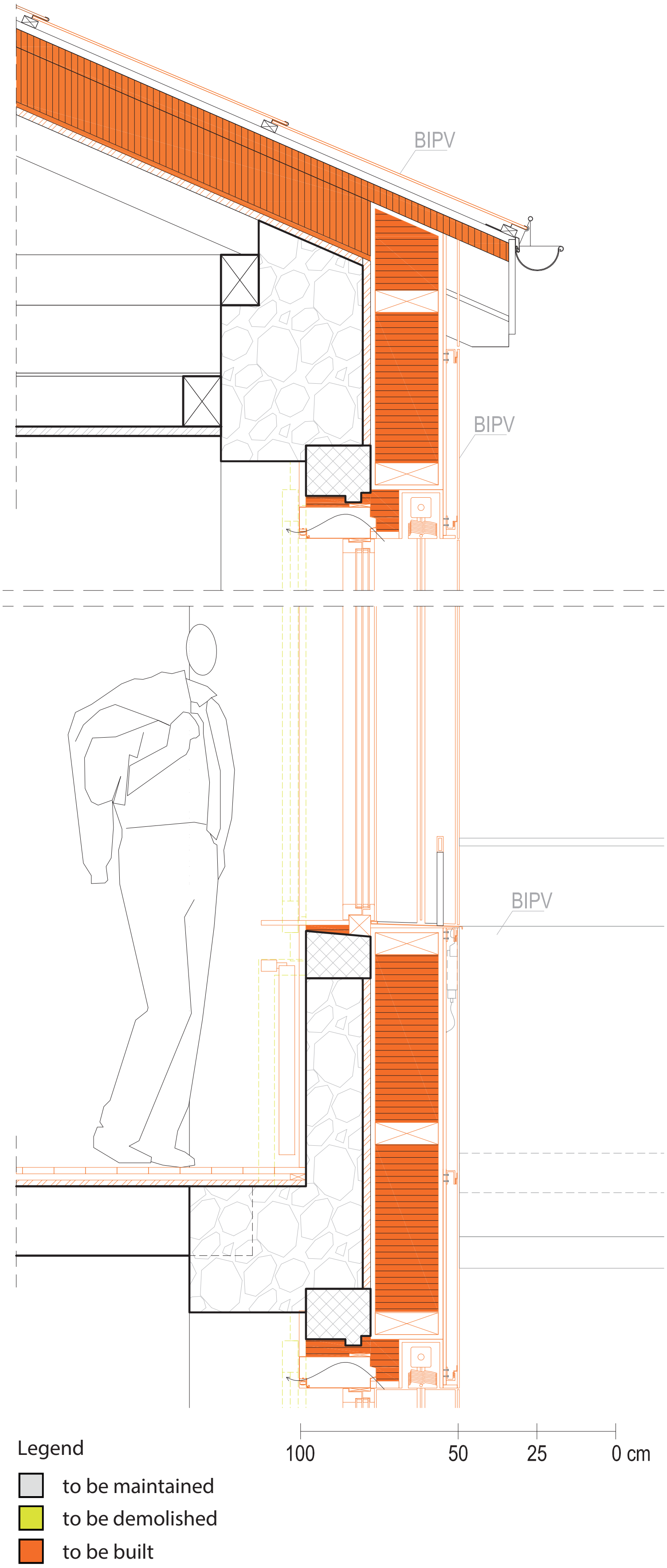
Internal floor (against non-heated space): Timber floor 5cm, Cement mortar 3 cm, Hallow slab / concrete 20 cm EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cast concrete slab 20 cm. Solar protections: Aluminium blinds 10 cm.

Balconies: Custom-size PV panels on railing, Light grey coloured film with η-11% (STC), New concrete slab 15 cm, new metallic profiles IPE 100.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)



Potentially active surfaces

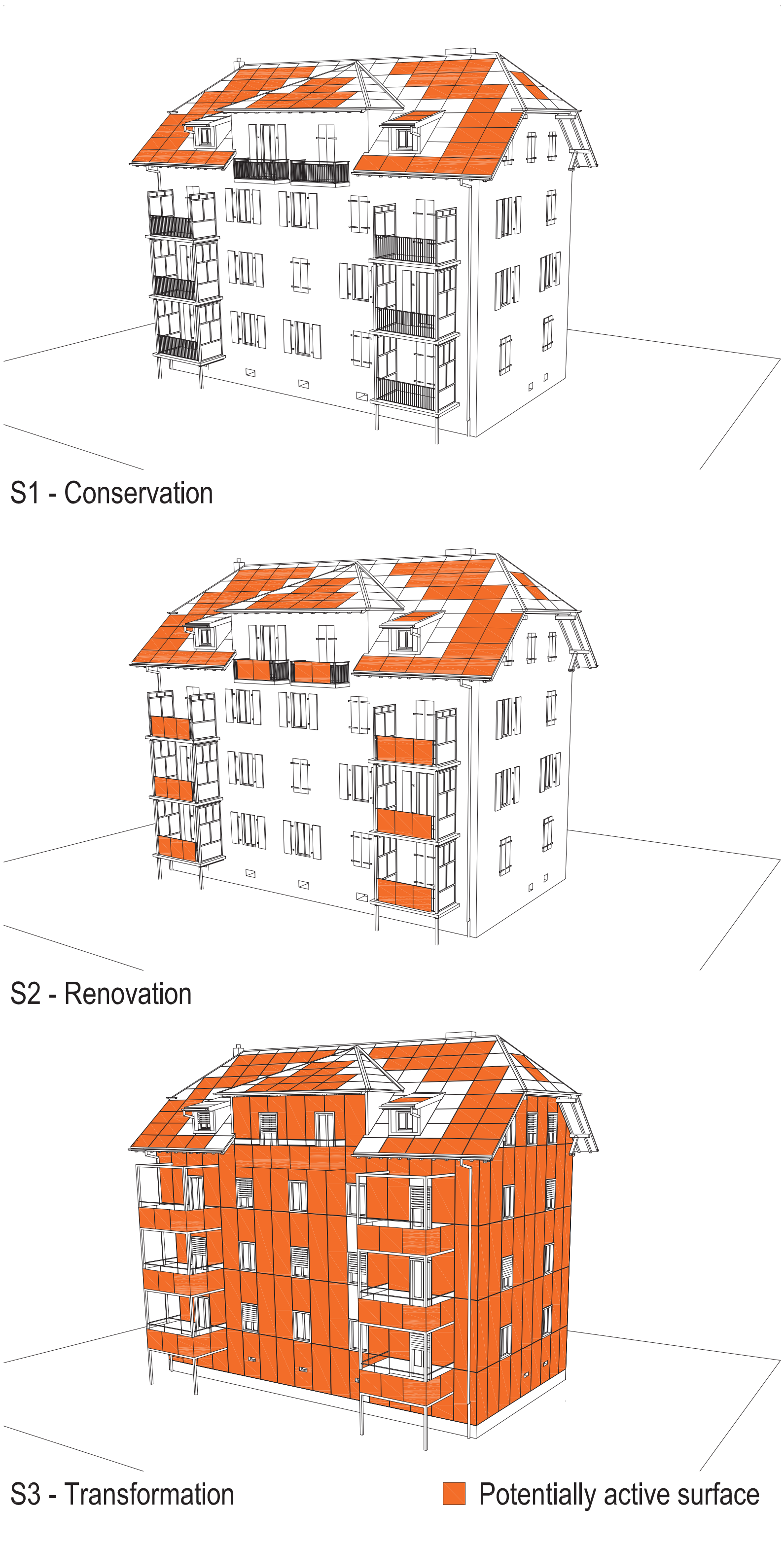


Figure 6-18. Potentially active surfaces detected for the different BIPV design scenarios, Archetype 1. Surfaces and equivalent power S1 (190 m^2 – 33 kWp), S2 (209 m^2 – 36 kWp), S3 (593 m^2 – 102 kWp).

Building envelope characteristics

S0 – Baseline	U-value
Roof – *ref. Dsi01**	**U- 0.25 W/m²·K**
Façade – *ref. Ws01**	**U- 0.25 W/m²·K**
Internal floor (against non-heated space) – *ref. Bsi07**	**U- 0.30 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-1.74 W/m²·K**
Openings **	**U- 1.30 W/m²·K**
Airtightness | *Infiltration rate*	*1.00 ACH*
S1 – BIPV Conservation	
Roof – *ref. Dsi01**	**U- 0.20 W/m²·K**
Façade – *ref. Ws01**	**U- 0.20 W/m²·K**
Internal floor (against non-heated space) – *ref. Bsi07**	**U- 0.30 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-1.74 W/m²·K**
Openings **	**U- 0.77 W/m²·K**
Airtightness | *Infiltration rate*	*0.70 ACH*
S2 – BIPV Renovation	
Roof – *ref. Dsi01**	**U- 0.19 W/m²·K**
Façade – *ref. Ws01**	**U- 0.19 W/m²·K**
Internal floor (against non-heated space) – *ref. Bsi07**	**U- 0.30 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-1.74 W/m²·K**
Openings **	**U- 0.77 W/m²·K**
Airtightness | *Infiltration rate*	*0.50 ACH*
S3 – BIPV Transformation	
Roof – *ref. Dsi01**	**U- 0.17 W/m²·K**
Façade – *ref. Wsi02**	**U- 0.17 W/m²·K**
Internal floor (against non-heated space) – *ref. Bsi07**	**U- 0.30 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-1.74 W/m²·K**
Openings **	**U- 0.77 W/m²·K**
Airtightness | *Infiltration rate*	*0.50 ACH*

Table 6-3. Final U-value of the different parts of the building envelope for each design scenario (E0, S0, S1, S2 and S3) for Archetype 1. Layers composition and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.3.

Thermal bridge analysis

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	-0.04	-0.04	-0.04	-0.03
TB2	+0.12	+0.14	+0.14	+0.15
TB3	+0.14	+0.13	+0.13	+0.11
TB4	-	-	-	-
TB6	**+0.43**	**+0.36**	**+0.35**	**+0.15**
TB7	-	-	-	-
TB8	+0.10	+0.09	+0.10	+0.10
TB9	+0.15	+0.14	+0.14	+0.15
TB10	**+0.20**	**+0.18**	**+0.18**	**+0.17**
TB11	-	-	-	ΔU +0.03 W/m²·K

Values in **bold** have been calculated using the THERM software, all other values are adopted from the Swiss catalogue of thermal bridges [Infomind Sàrl 2003].

Table 6-4. Linear thermal bridges values used for the Archetype 1. Detailed information in Annexe 10.1.3.

Requirements comparison

Archetype 1	**Oil / Gas boiler**				**Heat-Pump**		
Requirements	S0	S1	S2	S3	S1	S2	S3
SIA 380/1:2016	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie® 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-P 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-A 2017 Renovation	*NO*	*NO*	*NO*	**YES**	*NO*	**YES**	**YES**
2'000-watt society	*NO*	*NO*	*NO*	**YES**	**YES**	**YES**	**YES**
Construction	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
Exploitation	*NO*	*NO*	*NO*	*YES*	*YES*	*YES*	*YES*
PV > 10 Wp/m² of ERA	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

Table 6-5. Compliance check with energy requirements for Archetype 1.

6.4.2. Archetype 2

S0-Baseline | Archetype 2

Figure 6-19. Computer-generated image of scenario S0-Baseline, Archetype 2.

For the **S0-Baseline** scenario of this archetype (Figure 6-19, Figure 6-20 and Figure 6-21), the strategies adopted correspond to:

- Internal thermal insulation system.
- Replacement of existing windows and roller blinds.

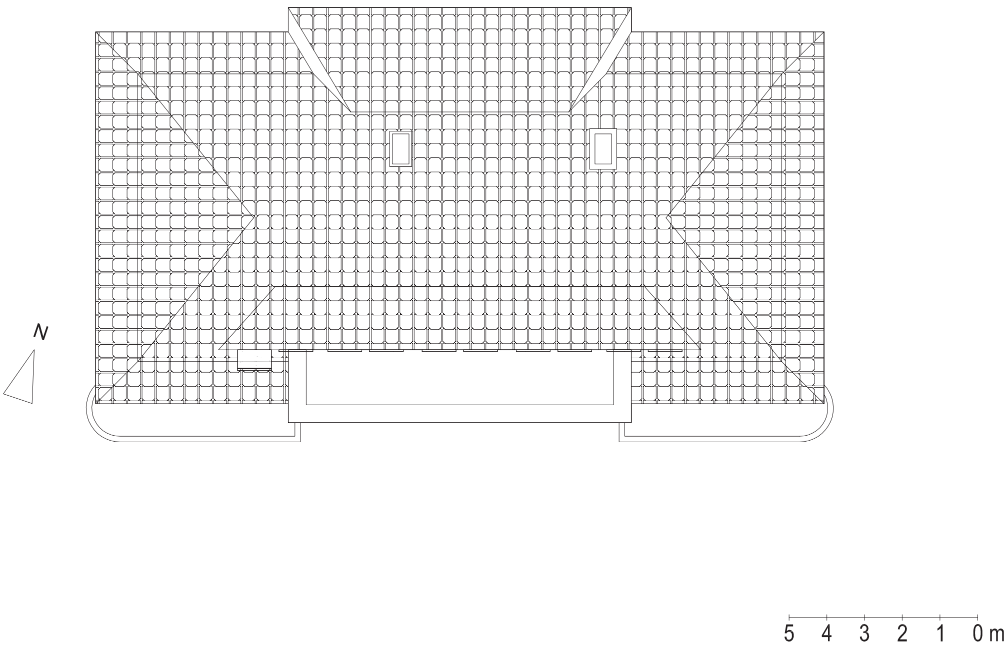


Figure 6-20. Design scenario S0 - Baseline, Archetype 2.

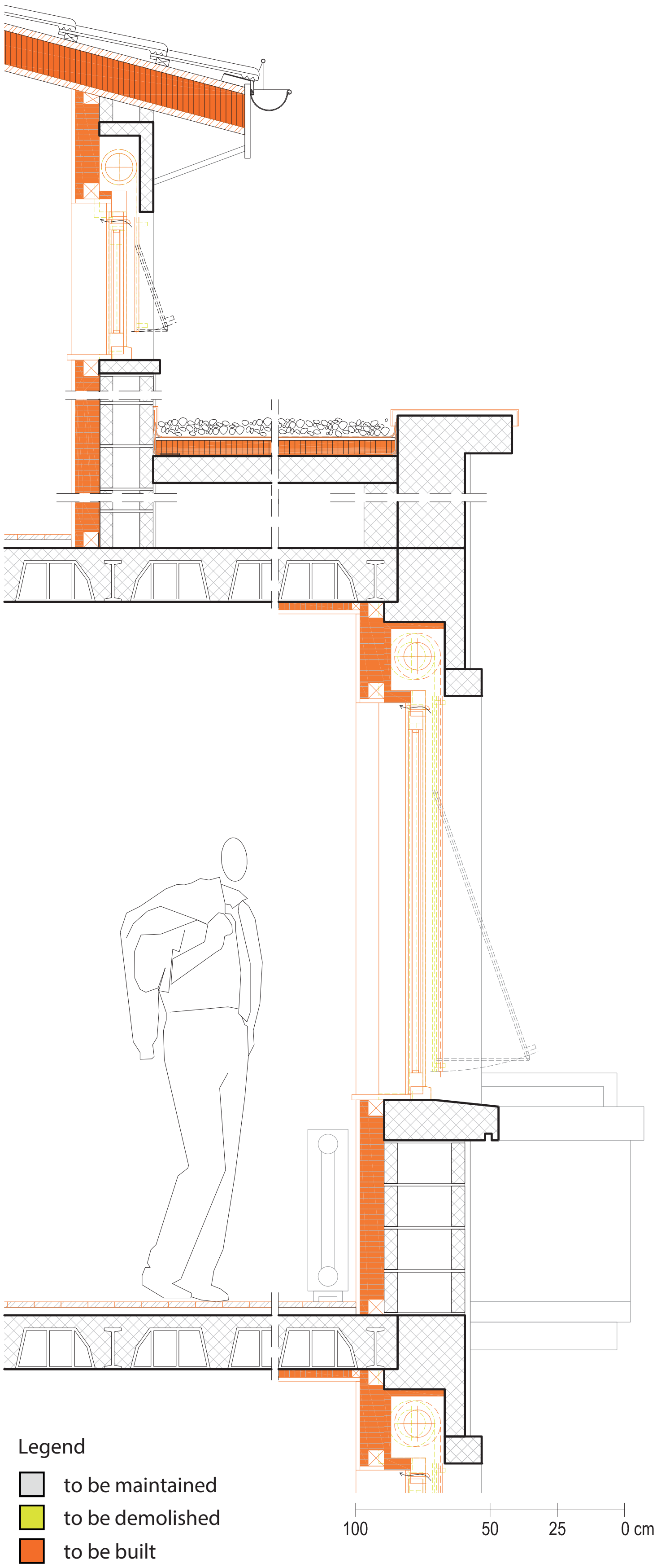


Figure 6-21. Façade constructive detail, **S0 - Baseline**, Archetype 2.

Roof: Tiles and slats 5 cm, Hardboard 2.5 cm, Oak lathing 5 cm, Mineral wool insulation 12 cm, Vapour barrier, Hardboard 2.5 cm.

Façade: Exterior plaster 2 cm, Cement hollow bricks masonry 35 cm, XPS extruded polystyrene 8+3 cm, Plasterboard 1.5 cm.

Internal floor (against non-heated space): Timber floor 5cm, Vapour barrier, Cement mortar 3 cm, Joists and terracotta slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cement mortar 3 cm, Cast concrete slab 15 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Cement slabs 18 cm.

Openings: PVC frame windows with double-glazing 4-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S1-Conservation | Archetype 2

Figure 6-22. Computer-generated image of scenario S1-Conservation, Archetype 2.

For the **S1–BIPV conservation** scenario (Figure 6-22, Figure 6-23 and Figure 6-24), in addition to the interventions of S0-Baseline, we propose to cover the roof using standard-size coloured BIPV elements, in order to maintain the building's expression. This additional strategy is:

- BIPV elements on the roof (147 m^2):
    - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
    - Standard size according to MegaSlate ® system with dummies elements to complete roof coverage.
    - Visual customisation using Terracotta coloured film.
    - Final performance estimation of about 14.5% in STC.

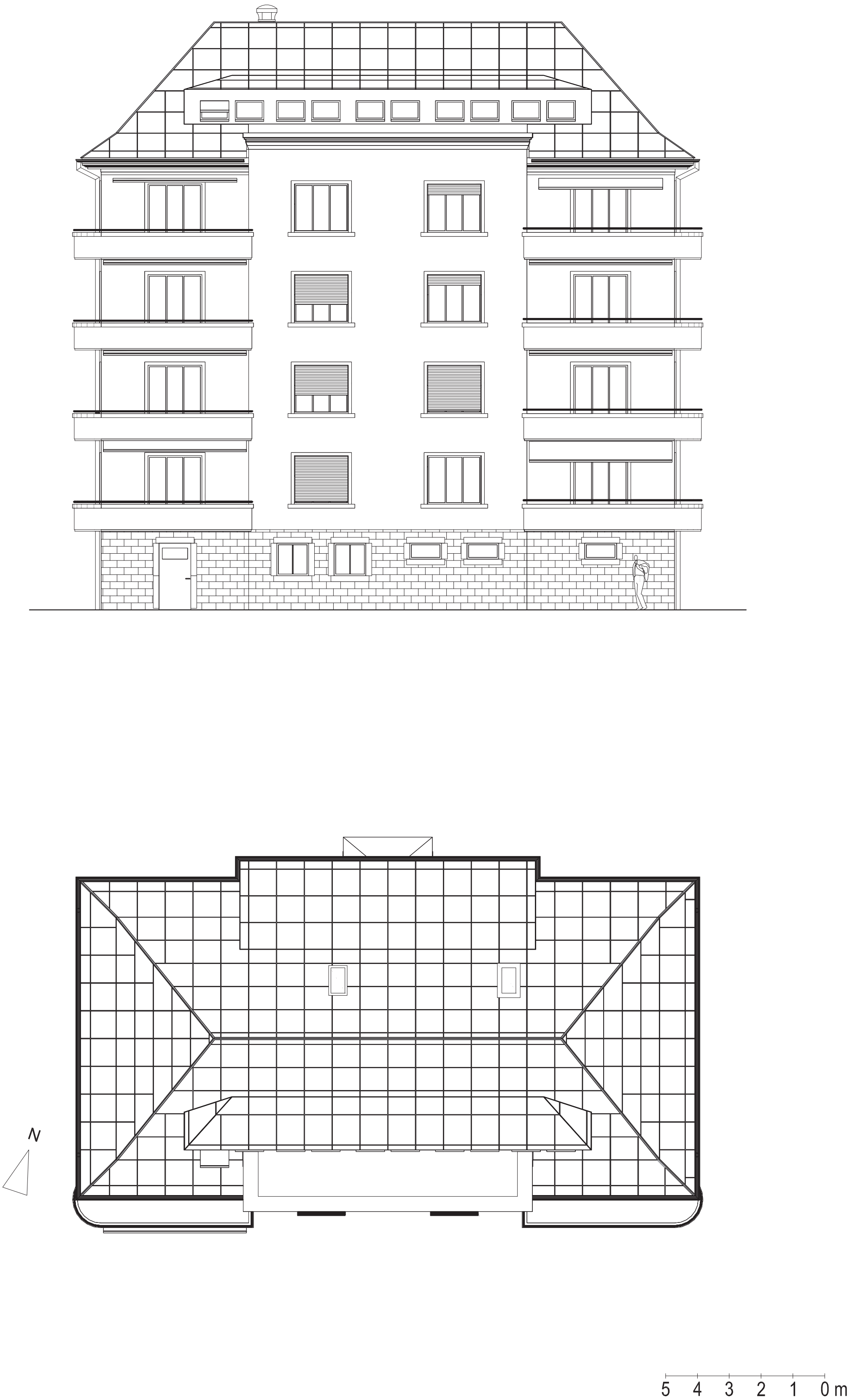


Figure 6-23. Design scenario S1 – BIPV Conservation, Archetype 2.

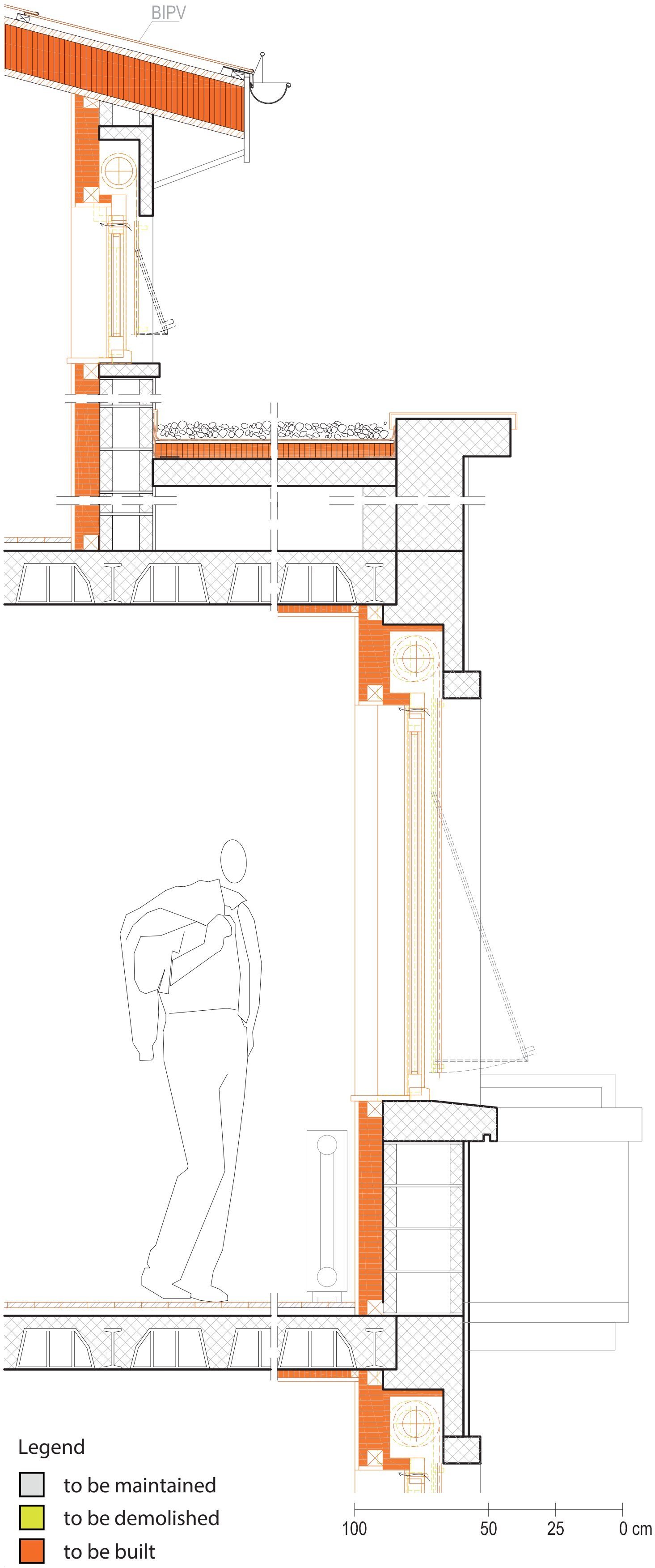


Figure 6-24. Façade constructive detail, S**1 – BIPV Conservation,** Archetype 2.

Roof: Standard-size PV panels, Terracotta coloured film with η-14.5% (STC), Hardboard 2.5 cm, Mineral wool insulation 15 cm, Vapour barrier, Hardboard 2.5 cm.

Façade: Exterior plaster 2 cm, Cement hollow bricks masonry 35 cm, XPS extruded polystyrene 8+6 cm, Plasterboard 1.5 cm.

Internal floor (against non-heated space): Timber floor 5cm, Vapour barrier, Cement mortar 3 cm, Joists and terracotta slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cement mortar 3 cm, Cast concrete slab 15 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Cement slabs 18 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S2-Renovation | Archetype 2

Figure 6-25. Computer- generated image of scenario S2-Renovation, Archetype 2.

For the S2–BIPV renovation scenario (Figure 6-25, Figure 6-26 and Figure 6-27), a more important insulation compared to S1 is implemented, along with the replacement of existing windows. The roof is covered with BIPV elements. The strategies adopted correspond to:

- External thermal insulation composite system (ETICS).
- Replacement of windows and roller blinds.
- BIPV elements on the roof (147 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Standard size according to Megaslate® system with dummies elements to complete roof coverage.
  - Visual customisation using Terracotta coloured film.
  - Final performance estimation of about 14.5% in STC.

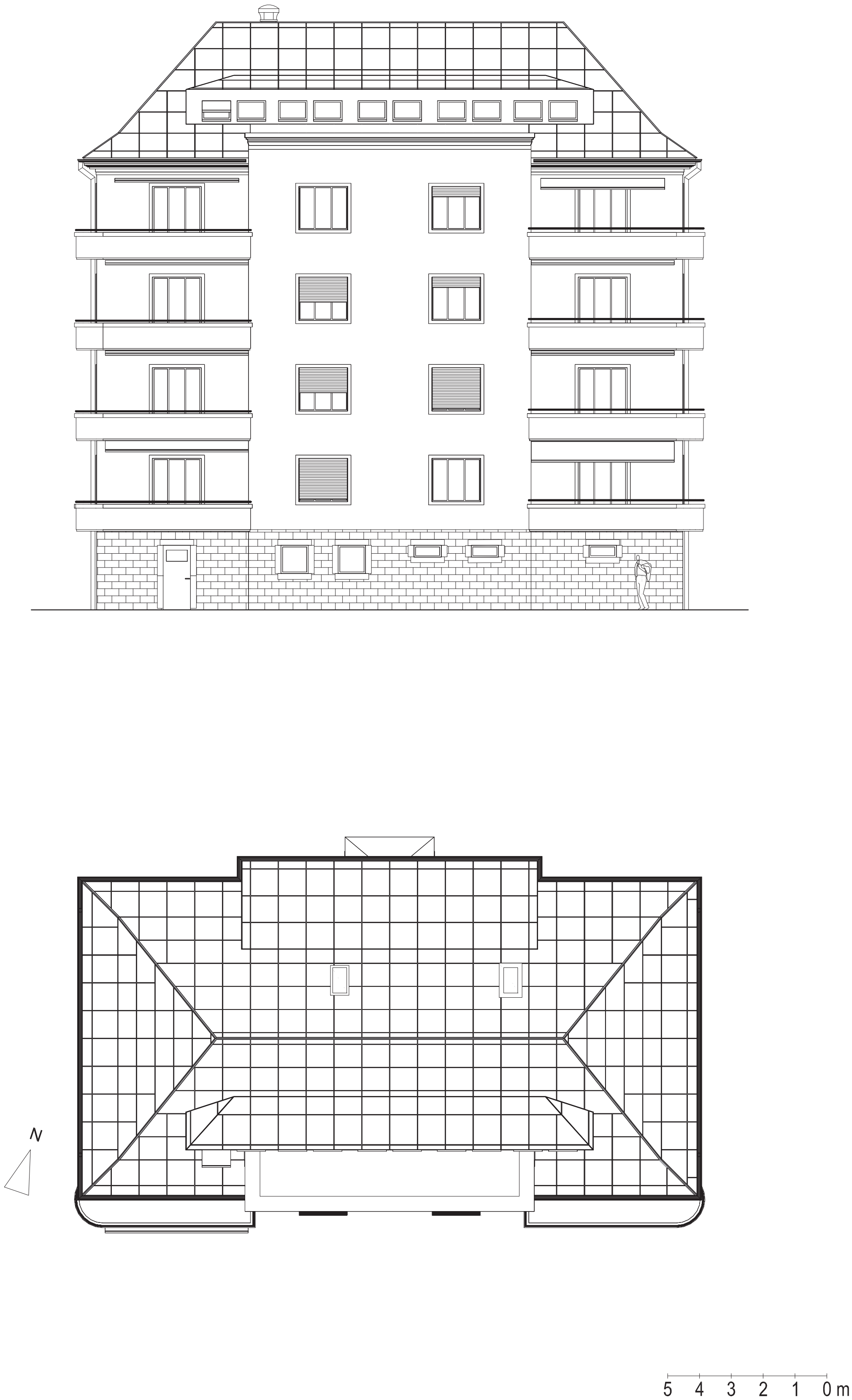


Figure 6-26. Design scenario S2 – BIPV Renovation, Archetype 2.

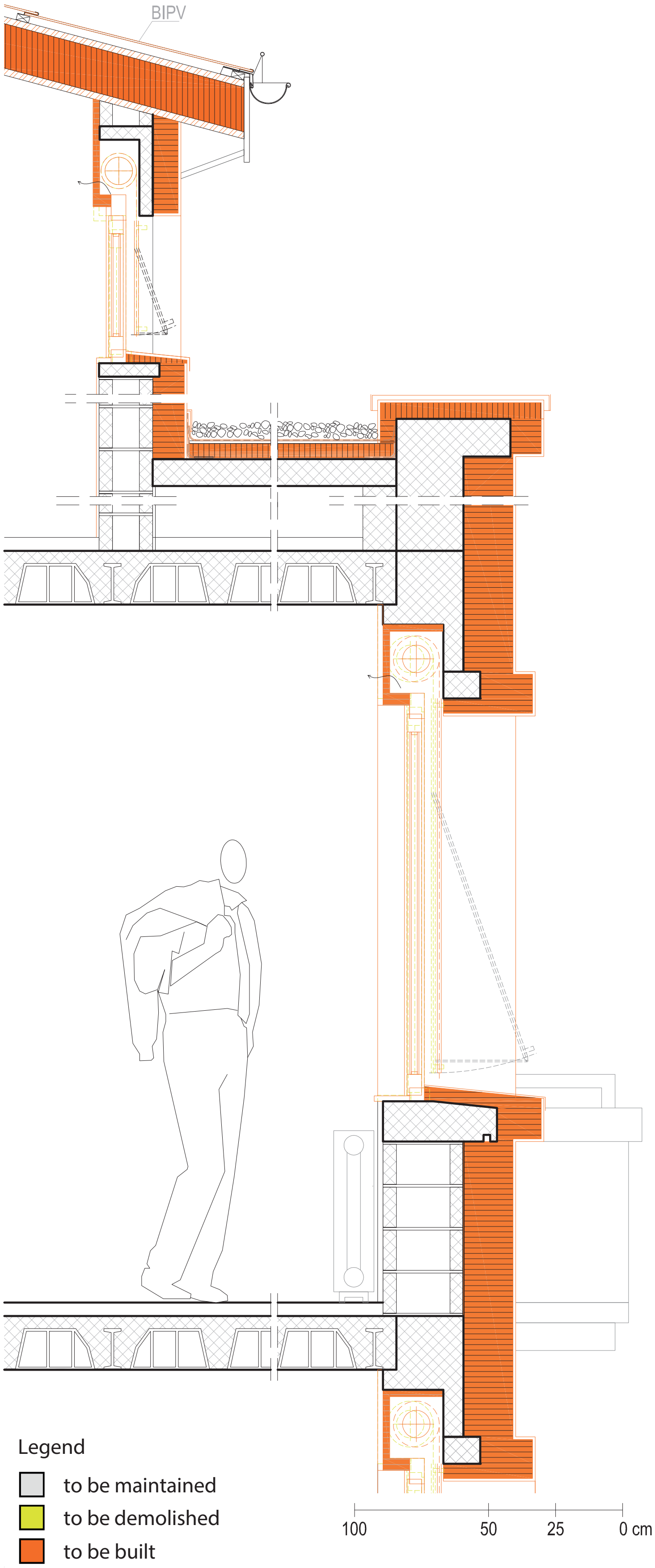


Figure 6-27. Façade constructive detail, **S2 – BIPV Renovation**, Archetype 2.

Roof: Standard-size PV panels, Terracotta coloured film with η-14.5% (STC), Hardboard 2.5 cm, Mineral wool insulation 16 cm, Vapour barrier, Hardboard 2.5 cm.

Façade: Synthetic plaster / reinforced mesh 1 cm, XPS extruded polystyrene 15 cm, Exterior plaster 2 cm, Cement hollow bricks masonry 35 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 5cm, Vapour barrier, Cement mortar 3 cm, Joists and terracotta slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cement mortar 3 cm, Cast concrete slab 15 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Cement slabs 18 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S3-Transformation | Archetype 2

Figure 6-28. Computer-generated image of scenario S3-Transformation, Archetype 2.

Finally, for the **S3–BIPV transformation** scenario (Figure 6-28, Figure 6-29 and Figure 6-30), we propose a prefabricated wooden structure façade to plug-in directly on the existing façade, including external insulation (ventilated façade), new windows, new prefabricated balconies and BIPV elements covering all opaque surfaces. The strategies adopted correspond to:

- Timber frame ventilated prefabricated façade system including all the envelope components and modulated according to the standard size of BIPV elements, prioritising low-carbon materials.

- New prefabricated balconies to avoid thermal bridge problems.
- BIPV elements on the roof (147 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Standard size according to Megaslate® system.
  - Visual customisation using Terracotta coloured film.
  - Final performance estimation of about 14.5% in STC.
- BIPV elements in façade (348 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3'800 mm, width 50-2'400 mm) using 6" standard size solar cells **[metsolar 2018a]** and minimising the variety of dimensions to simplify the electric connections.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.

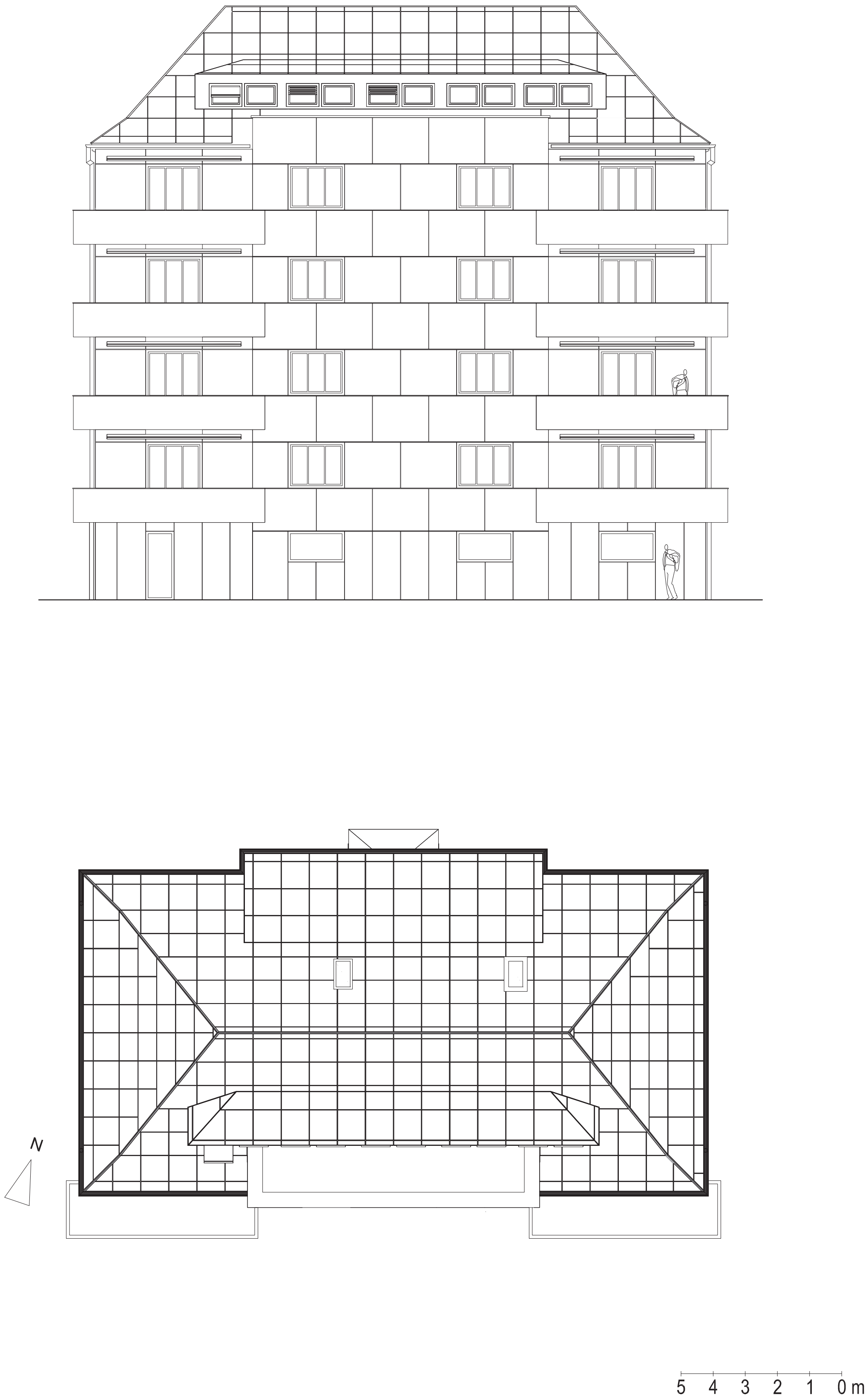


Figure 6-29. Design scenario S3 – BIPV Transformation, Archetype 2.

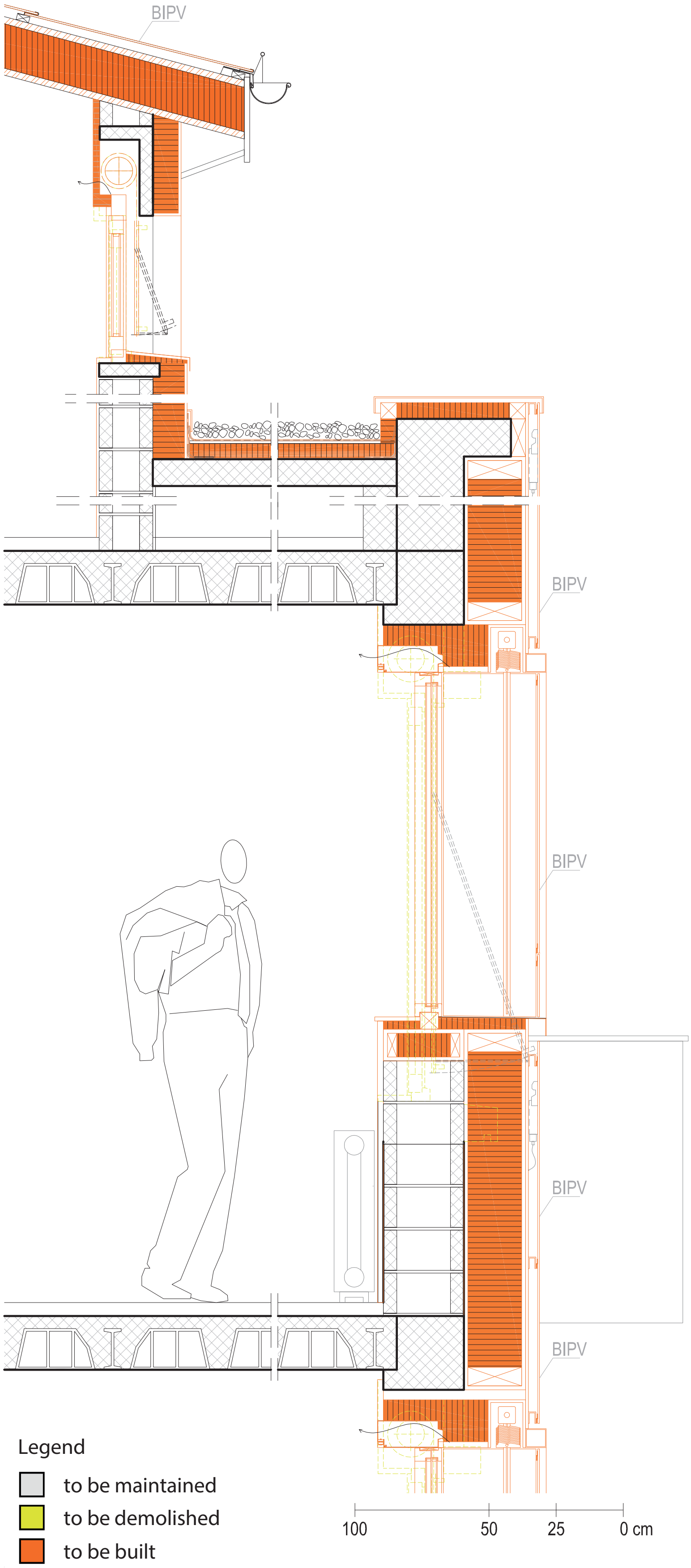


Figure 6-30. Façade constructive detail, **S3 – BIPV Transformation**, Archetype 2.

Roof: Standard-size PV panels, Terracotta coloured film with η-14.5% (STC), Hardboard 2.5 cm, Mineral wool insulation 20 cm, Vapour barrier, Hardboard 2.5 cm.

Façade: Custom-size PV panels, Light grey coloured film with η-11% (STC), Air gap 5 cm, Wood particle board 1.5 cm, EPS expanded polystyrene (100% recycled) 16 cm, Wood particle board 1.5 cm, Exterior plaster 2 cm, Cement hollow bricks masonry 35 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 5cm, Vapour barrier, Cement mortar 3 cm, Joists and terracotta slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Cement mortar 3 cm, Cast concrete slab 15 cm.

Solar protections: Aluminium blinds 10 cm.

Balconies: Prefabricated wooden balcony with slab of 15 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

Potentially active surfaces

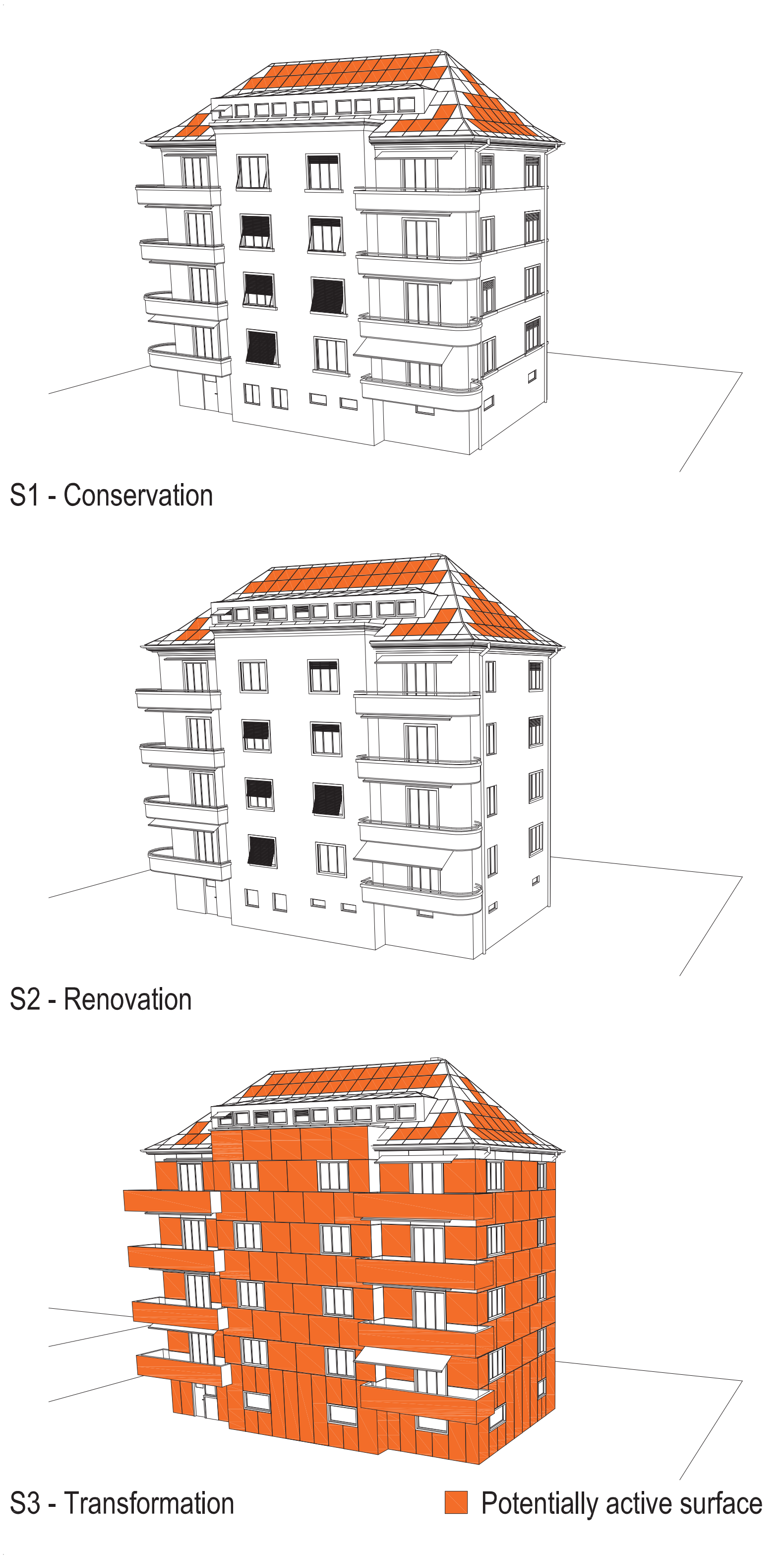


Figure 6-31. Potentially active surfaces detected for the different BIPV design scenarios, Archetype 2. Surfaces and equivalent power S1 (147 m^2 – 25 kWp), S2 (147 m^2 – 25 kWp), S3 (821 m^2 – 141 kWp).

Building envelope characteristics

S0 – Baseline	U-value
Roof – *ref. Dsi01**	**U- 0.25 W/m²·K**
Façade – *ref. Ws03**	**U- 0.25 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs06a**	**U-0.29 W/m²·K**
External floor (ground) **–** *ref. Bs06a**	**U-1.63 W/m²·K**
Openings **	**U- 1.30 W/m²·K**
Airtightness | Infiltration rate	*1.50 ACH*
S1 – BIPV Conservation	
Roof – *ref. Dsi01**	**U- 0.20 W/m²·K**
Façade – *ref. Ws03**	**U- 0.20 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs06a**	**U-0.29 W/m²·K**
External floor (ground) – *ref. Bs06a**	**U- 1.63 W/m2·K**
Openings **	**U- 0.77 W/m²·K**
Airtightness | Infiltration rate	*1.50 ACH*
S2 – BIPV Renovation	
Roof – *ref. Dsi01**	**U- 0.19 W/m²·K**
Façade – *ref. Ws01**	**U- 0.19 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs06a**	**U-0.29 W/m²·K**
External floor (ground) – *ref. Bs06a**	**U-1.63 W/m2·K**
Openings **	**U- 0.77 W/m²·K**
Airtightness | Infiltration rate	*0.70 ACH*
S3 – BIPV Transformation	
Roof – *ref. Dsi01**	**U- 0.17 W/m²·K**
Façade – *ref. Wsi02**	**U- 0.17 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs06a**	**U-0.29 W/m²·K**
External floor (ground) – *ref. Bs06a**	**U-1.63 W/m2·K**
Openings **	**U- 0.77 W/m²·K**
Airtightness | Infiltration rate	*0.50 ACH*

Table 6-6. Final U-value of the different parts of the building envelope for each design scenario (E0, S0, S1, S2 and S3) for Archetype 2. Layers composition and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.4.

Thermal bridge analysis

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	-0.09	-0.07	-0.04	-0.03
TB2	-0.04	+0.01	+0.14	+0.15
TB3	+0.14	+0.13	+0.13	+0.11
TB4	+0.12	+0.13	+0.13	+0.15
TB6	**+1.23**	**+1.23**	**+0.94**	**+0.44**
TB7	+0.22	+0.23	+0.25	+0.25
TB8	+0.15	+0.15	+0.14	+0.15
TB9	+0.06	+0.08	+0.11	+0.12
TB10	**+0.80**	**+0.80**	**+0.88**	**+0.18**
TB11	-	-	-	ΔU +0.03 W/m²·K

Values in **bold** have been calculated using the THERM software, all other values are adopted from the Swiss catalogue of thermal bridges [Infomind Sàrl 2003].

Table 6-7. Linear thermal bridges values used for the Archetype 2. Detailed information in Annexe 10.1.4.

Requirements comparison

Archetype 2	**Oil / Gas boiler**				**Heat-Pump**		
Requirements	S0	S1	S2	S3	S1	S2	S3
SIA 380/1:2016	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie® 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-P 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-A 2017 Renovation	*NO*	*NO*	*NO*	**YES**	*NO*	*NO*	**YES**
2'000-watt society	*NO*	*NO*	*NO*	*NO*	**YES**	**YES**	**YES**
Construction	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
Exploitation	*NO*	*NO*	*NO*	*NO*	*YES*	*YES*	*YES*
PV > 10 Wp/m² of ERA	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

Table 6-8. Compliance check with energy requirements for Archetype 2.

6.4.3. Archetype 3

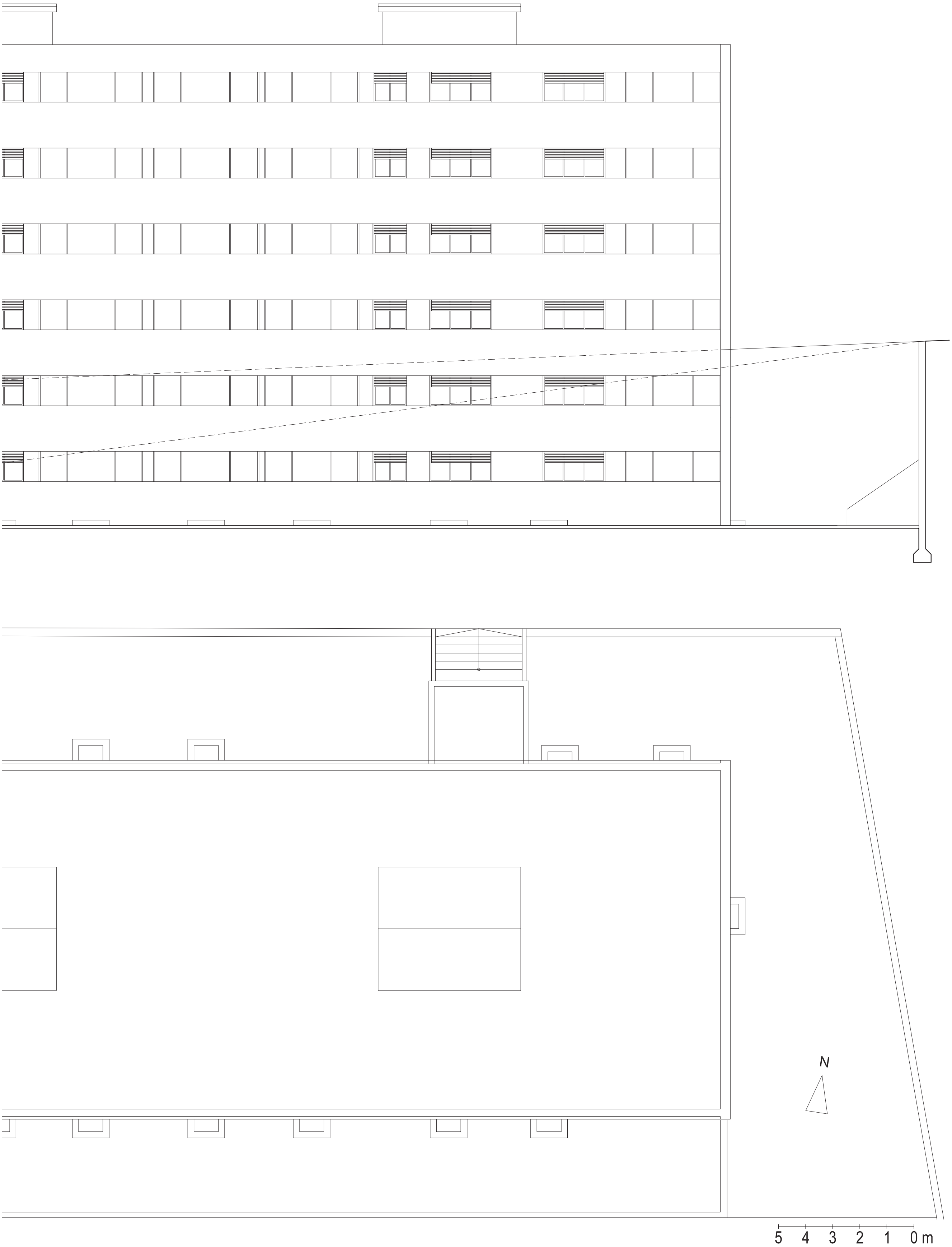
S0-Baseline | Archetype 3

Figure 6-32. Computer-generated image of scenario S0-Baseline, Archetype 3.

For the **S0-Baseline** scenario of this archetype (Figure 6-32, Figure 6-33 and Figure 6-34), the strategies adopted correspond to:

- External thermal insulation composite system (ETICS).
- Replacement of existing windows and roller blinds.

Figure 6-33. Design scenario S0-Baseline, Archetype 3.


N
5 4 3 2 1 0 m

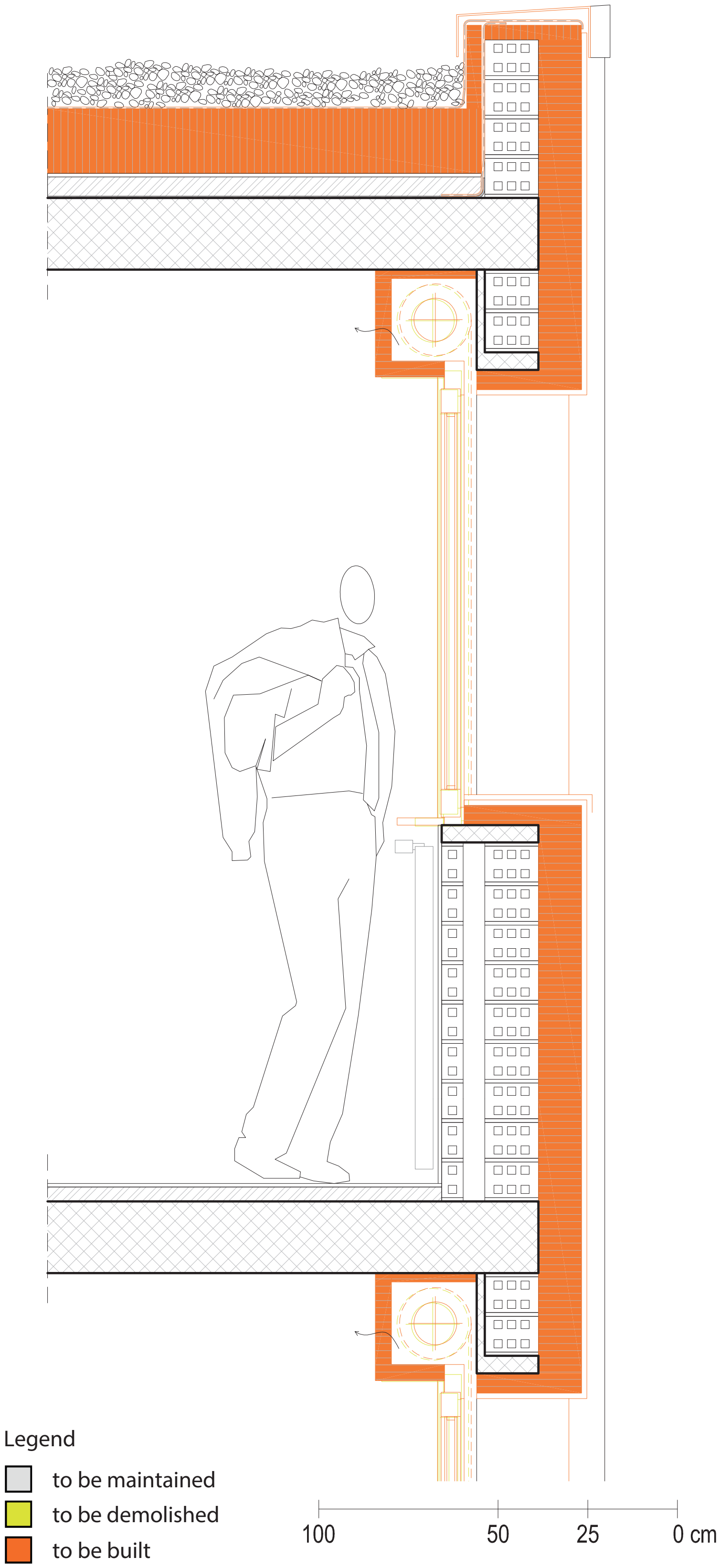


Figure 6-34. Façade constructive detail, **S0 - Baseline**, Archetype 3.

Roof: Gravel 5-10 cm, Bitumen 0.4 cm, EPS extruded polystyrene 15 cm, Reinforced concrete slab 20 cm, Bitumen 0.4 cm.

Façade: Synthetic plaster / reinforce. mesh 1 cm, XPS extruded polystyrene 12 cm, Ceramic brick 15 cm, Air gap 6 cm, Ceramic brick 6 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement screed 3 cm, Reinforced concrete slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Reinforced concrete slab 20 cm, XPS extruded polystyrene 4 cm.

Solar protections: Wooden roller shutter 3cm.

Balconies: Reinforced concrete slab 20 cm.

Openings: PVC frame windows with double-glazing 4-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S1-Conservation | Archetype 3

Figure 6-35. Computer-generated image of scenario S1-Conservation, Archetype 3.

For the **S1–BIPV conservation** scenario (Figure 6-35, Figure 6-36 and Figure 6-37), in addition to the interventions of S0-Baseline, we propose to cover the roof using doubled-oriented BAPV panels and the opaque part between the windows using coloured custom-size BIPV elements, in order to maintain the building's expression. The added strategies adopted correspond to:

- BAPV elements on the flat roof (384 m^2):
  - South-oriented PV panels with mono-Si cells technology (with an efficiency of 20% in STC).
  - Standard size modules.

- BIPV elements in façade (between windows) (78 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3800 mm, width 50-2400 mm) using 6″ standard size solar cells **[metsolar 2018b]**.
  - Visual customisation using dark grey coloured film.
  - Final performance estimation of about 13% in STC.

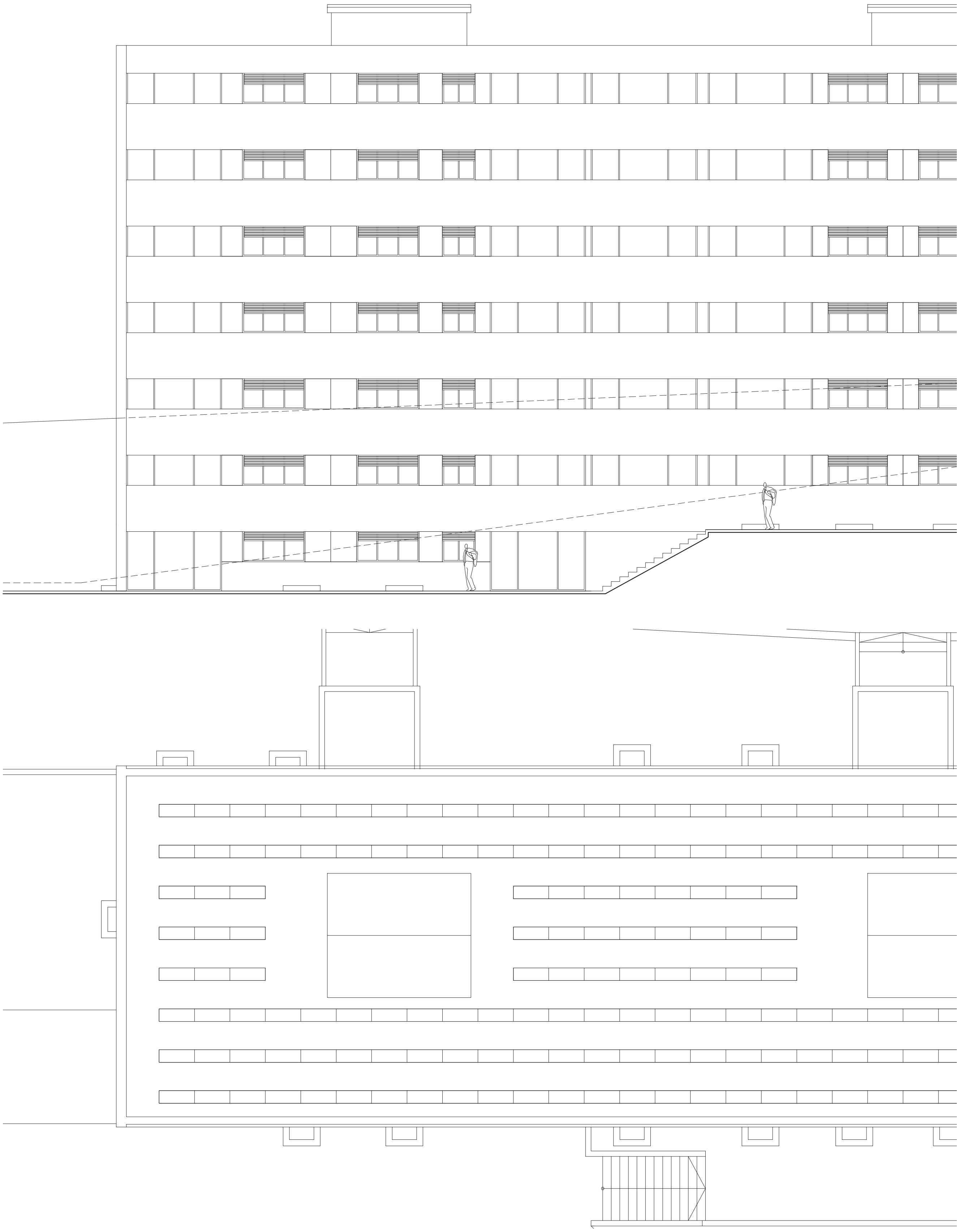
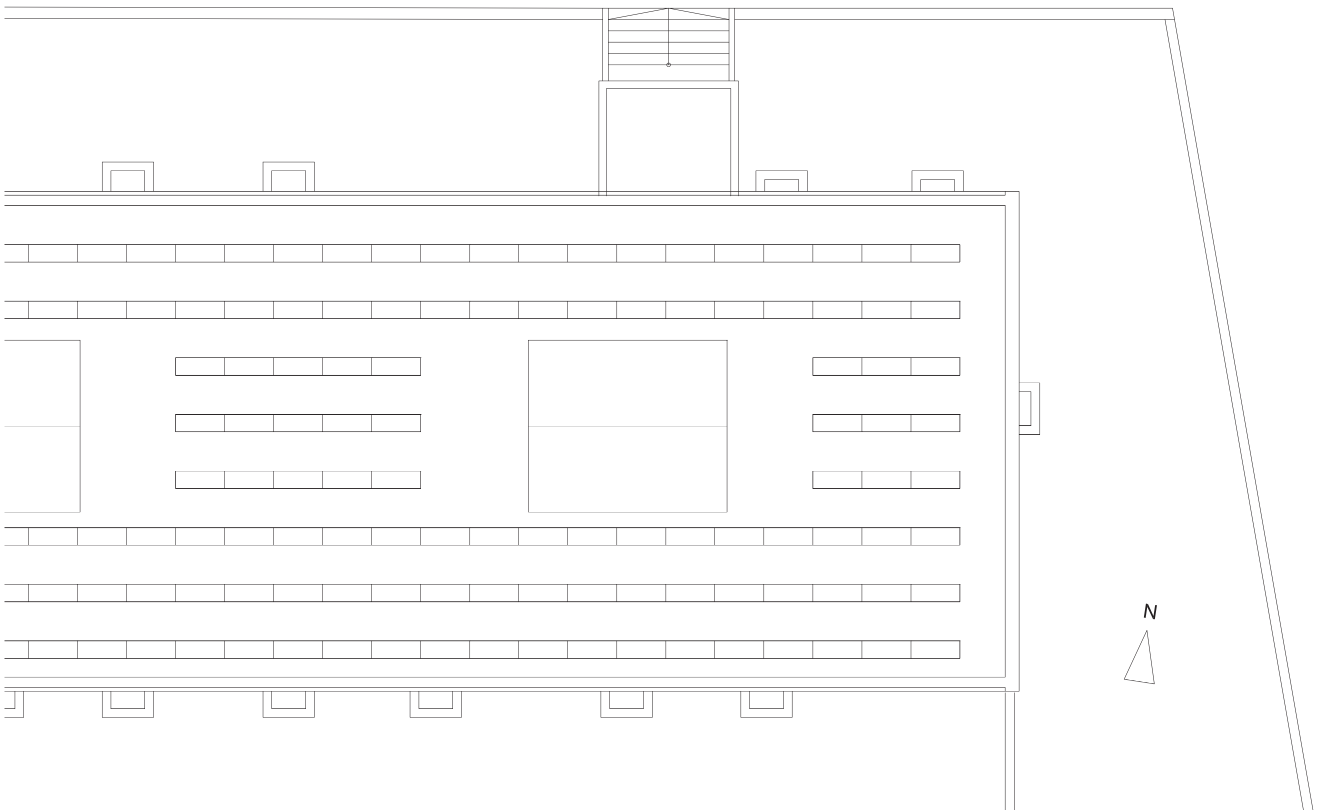


Figure 6-36. Design scenario S1-Conservation, Archetype 3.


N
5 4 3 2 1 0 m

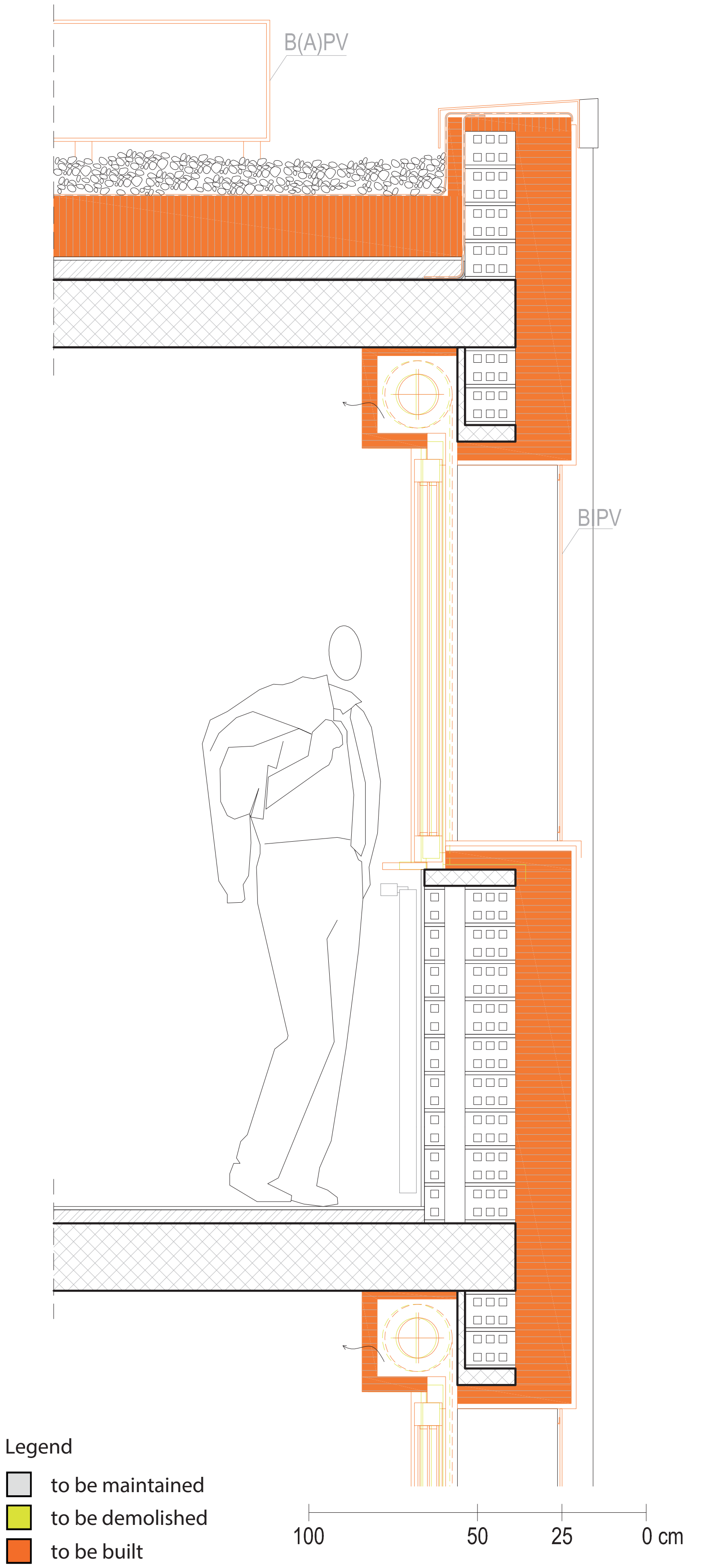


Figure 6-37. Façade constructive detail, **S1-Conservation, Archetype 3.**

Roof: B(A)PV panels (east-west oriented), Gravel 5-10 cm, Bitumen 0.4 cm, EPS extruded polystyrene 18 cm, Reinforced concrete slab 20 cm, Bitumen 0.4 cm.

Façade: Synthetic plaster / reinforce. mesh 1 cm, XPS extruded polystyrene 16 cm, Ceramic brick 15 cm, Air gap 6 cm, Ceramic brick 6 cm, Gypsum plaster 1 cm.

Between windows (additional layers): Custom-size PV panels, dark grey coloured film with η-13% (STC), Air gap 5 cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement screed 3 cm, Reinforced concrete slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Reinforced concrete slab 20 cm, XPS extruded polystyrene 4 cm.

Solar protections: Wooden roller shutter 3cm.

Balconies: Reinforced concrete slab 20 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S2-Renovation | Archetype 3

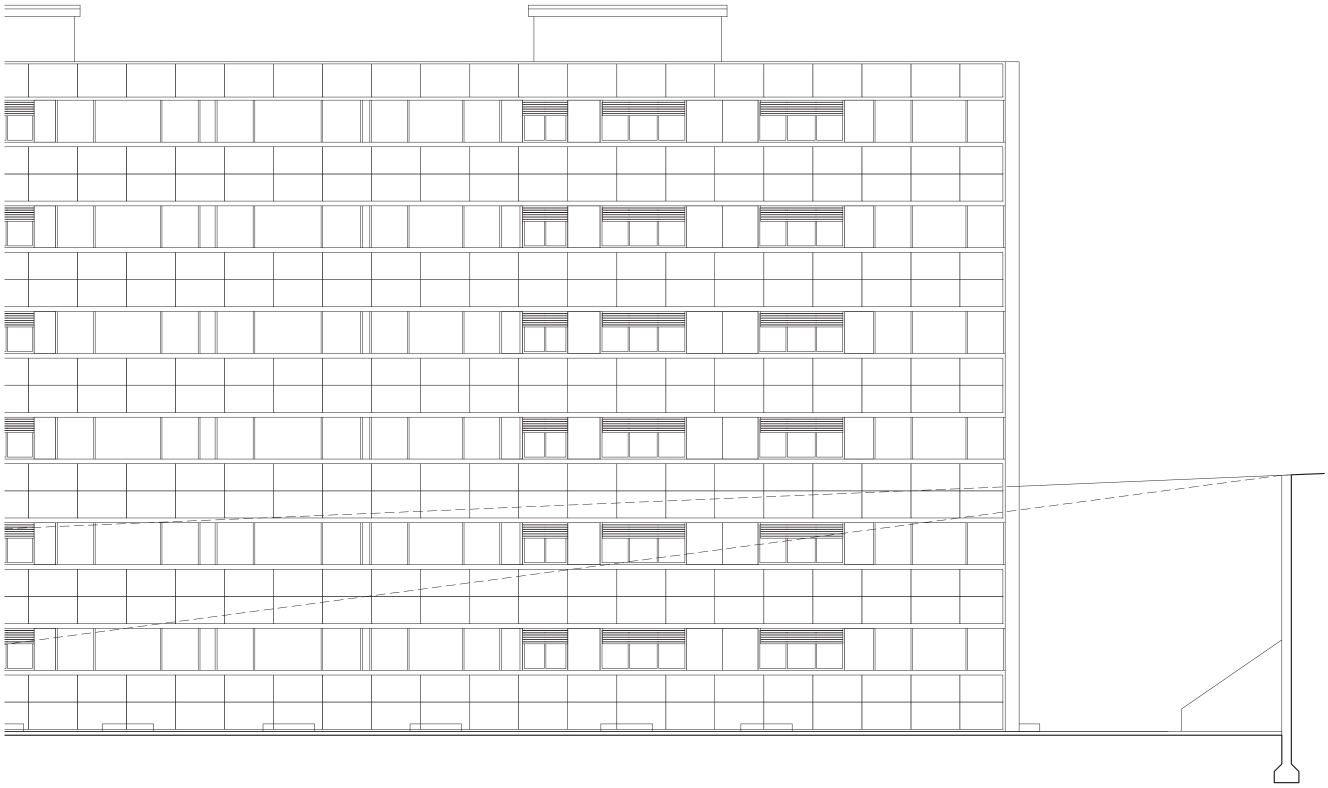
Figure 6-38. Computer-generated image of scenario S2-Renovation, Archetype 3.

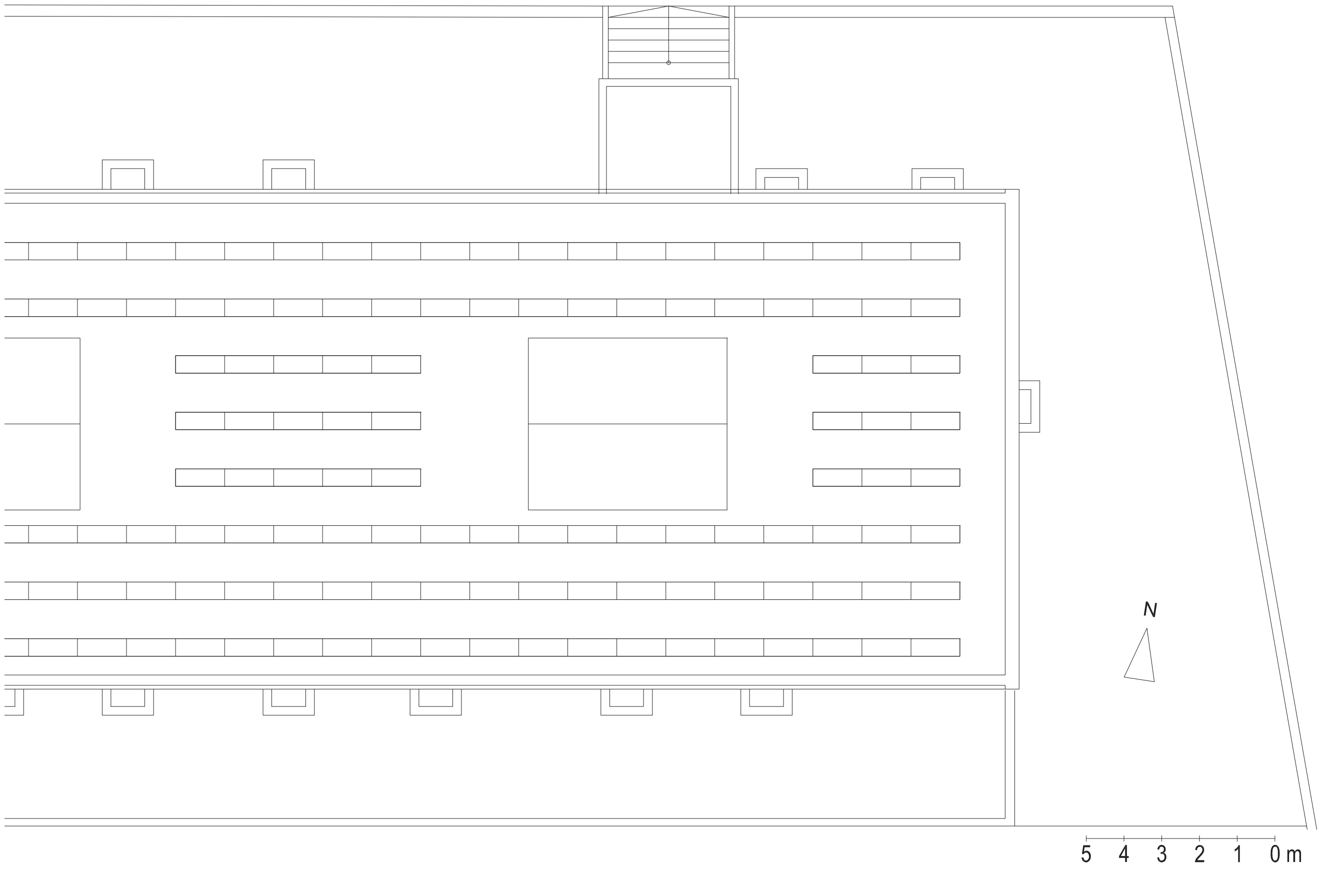
For the S2–BIPV renovation scenario (Figure 6-38, Figure 6-39 and Figure 6-40), an externally insulated ventilated façade system is implemented, including the replacement of existing windows, covering the roof with standard BAPV panels, and placing BIPV elements on the opaque surfaces of the façade, in a way to maintain the main lines of the building's expression. The strategies adopted correspond to:

- External thermal insulation composite system (ETICS).
- Replacement of windows and roller blinds.
- BAPV elements on the flat roof (384 m^2):
  - South-oriented PV panels with mono-Si cells technology (with an efficiency of 20% in STC).
  - Standard size modules.

- BIPV elements in façade (between windows) (78 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3800 mm, width 50-2400 mm) using 6″ standard size solar cells **[metsolar 2018b]**.
  - Visual customisation using dark grey coloured film.
  - Final performance estimation of about 13% in STC.
- BIPV elements in façade (horizontal banners) (1’064 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Standard size according to Megaslate® system.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.

Figure 6-39. Design scenario S2 – BIPV Renovation, Archetype 3.




N
5 4 3 2 1 0 m

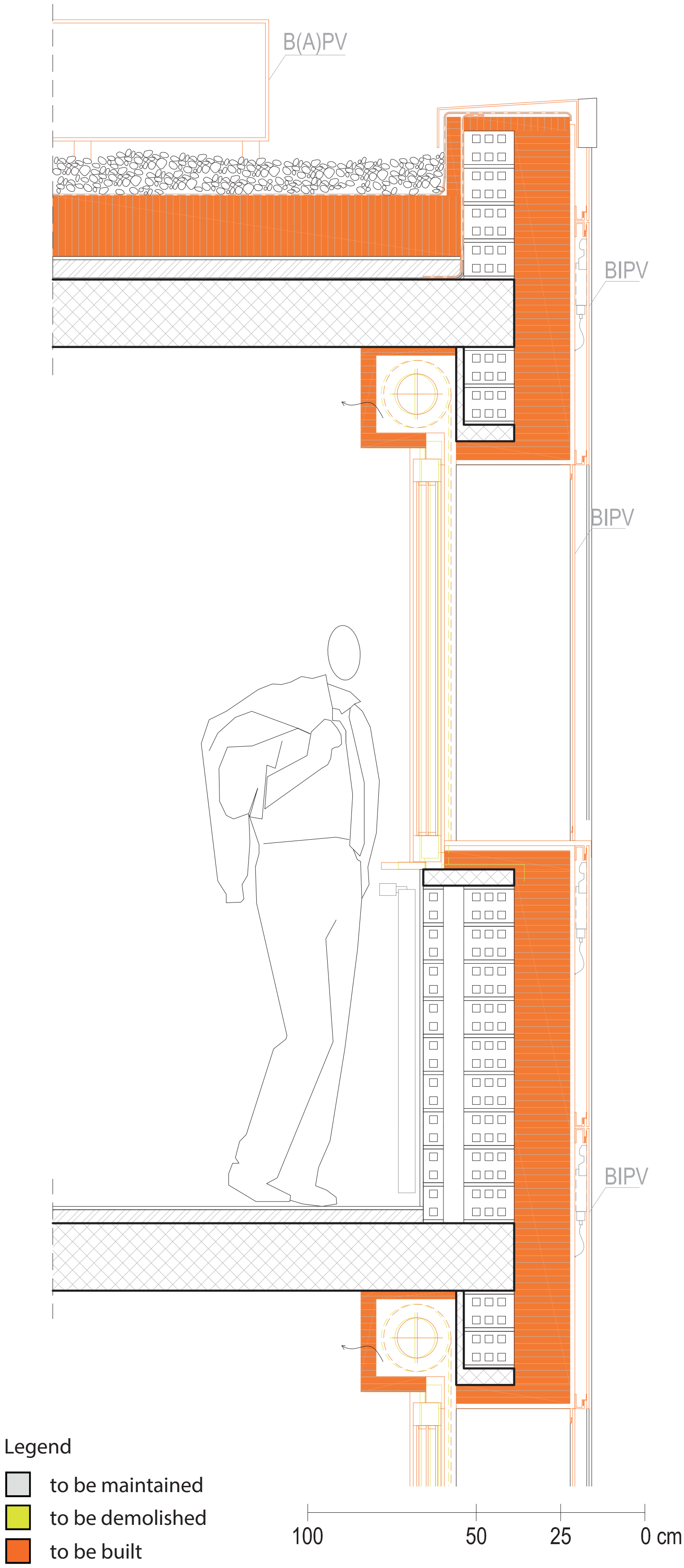


Figure 6-40. Façade constructive detail, **S2 – BIPV Renovation**, Archetype 3.

Roof: B(A)PV panels (east-west oriented), Gravel 5-10 cm, Bitumen 0.4 cm, EPS extruded polystyrene 20 cm, Reinforced concrete slab 20 cm, Bitumen 0.4 cm.

Façade: Custom-size PV panels, dark / light grey coloured film with η-13% / 11% (STC), Air gap 5 cm, Synthetic plaster / reinforce. mesh 1 cm, XPS extruded polystyrene 15 cm, Ceramic brick 15 cm, Air gap 6 cm, Ceramic brick 6 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement screed 3 cm, Reinforced concrete slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Reinforced concrete slab 20 cm, XPS extruded polystyrene 4 cm.

Solar protections: Wooden roller shutter 3cm.

Balconies: Reinforced concrete slab 20 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S3-Transformation | Archetype 3

Figure 6-41. Computer-generated image of scenario S3-Transformation, Archetype 3.

Finally, for the **S3–BIPV transformation** scenario (Figure 6-41, Figure 6-42 and Figure 6-43), as for the previous archetypes, a prefabricated wooden structure façade is implemented, plugging-in directly on the existing façade, and including external insulation (ventilated façade), new windows and BIPV elements covering all opaque surfaces. The strategies adopted correspond to:

- Timber frame ventilated prefabricated façade system including all the envelope components and modulated according to the standard size of BIPV elements, prioritising low-carbon materials.
- BAPV elements on the flat roof (384 m^2):
  - South-oriented PV panels with mono-Si cells technology (with an efficiency of 20% in STC).
  - Standard size modules.

- BIPV elements in façade (1’461 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Prioritising standard size according to Megaslate® system but with the possibility to use bigger panels respecting manufacturers recommendations for glass/glass modules (length 50-3’800 mm, width 50-2’400 mm) using 6″ standard size solar cells **[metsolar 2018a]** and minimising the variety of dimensions to simplify the electric connections.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.

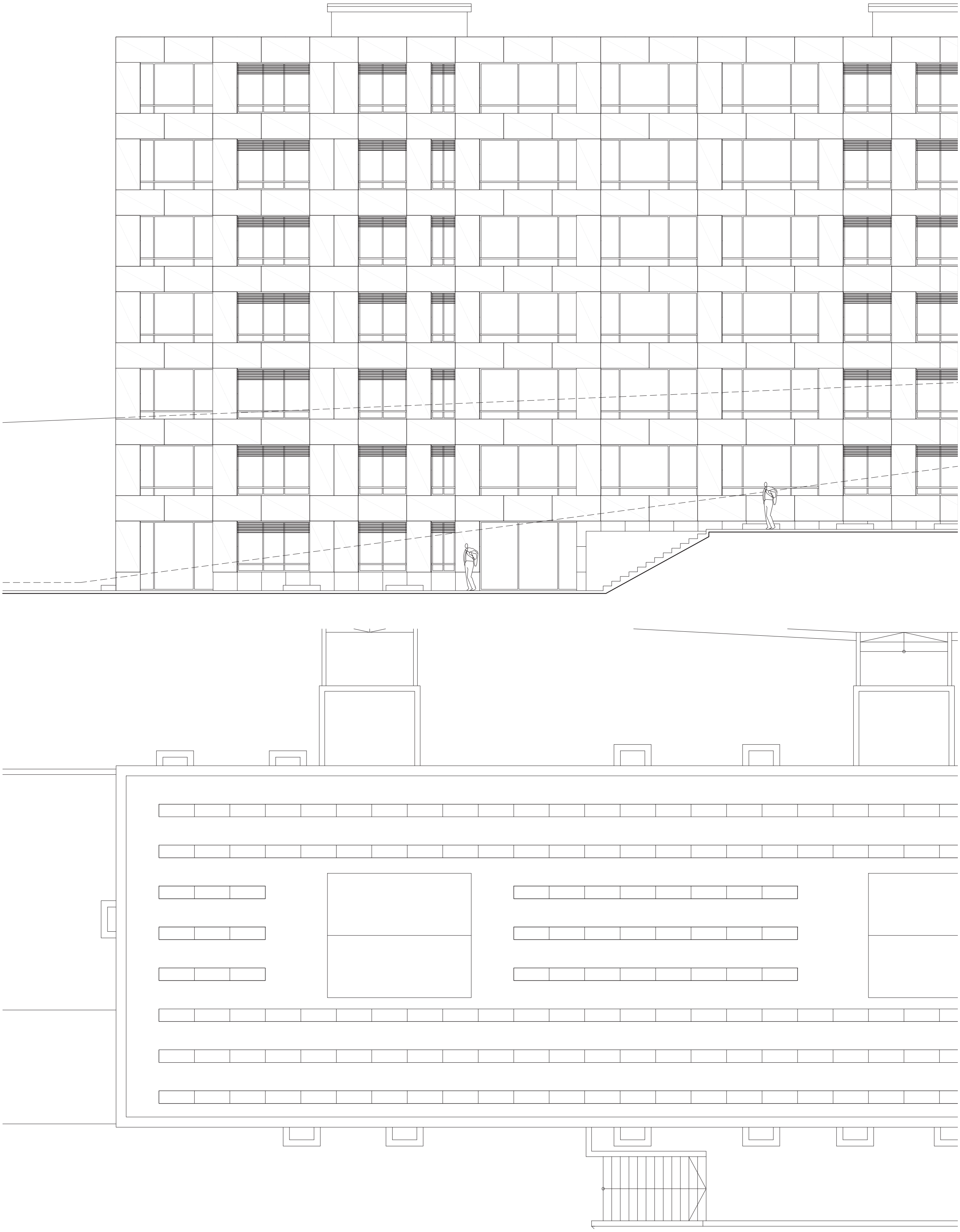
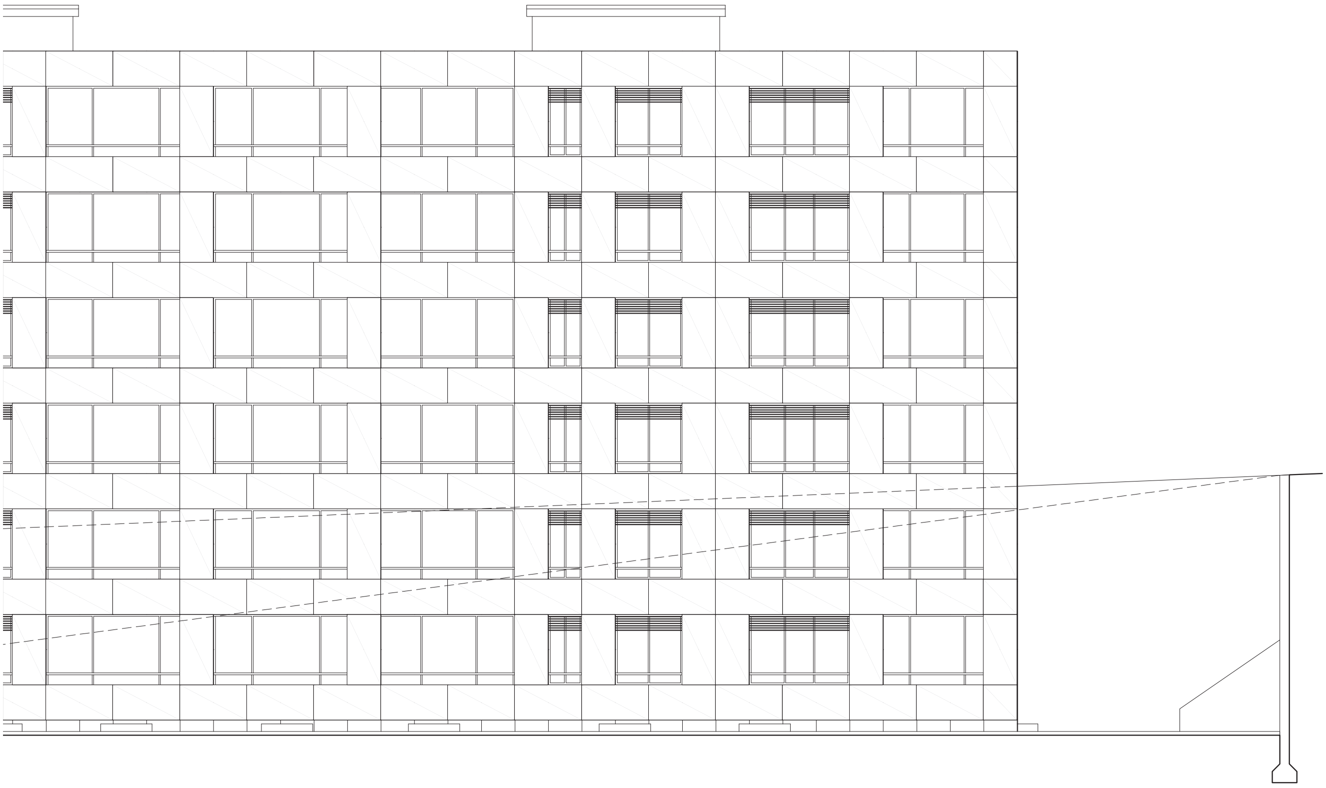
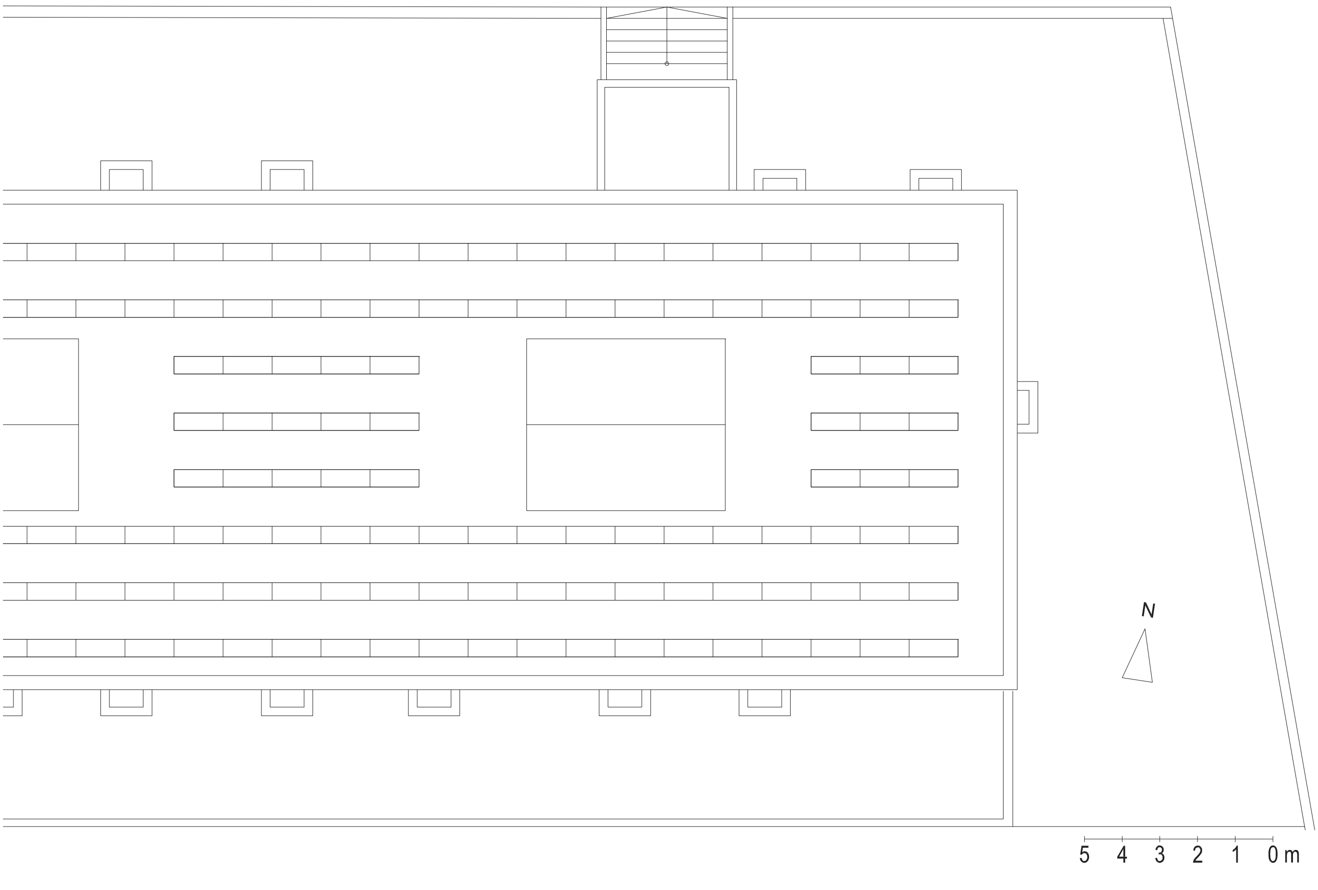


Figure 6-42. Design scenario S3 – BIPV Transformation, Archetype 3..




N
5 4 3 2 1 0 m

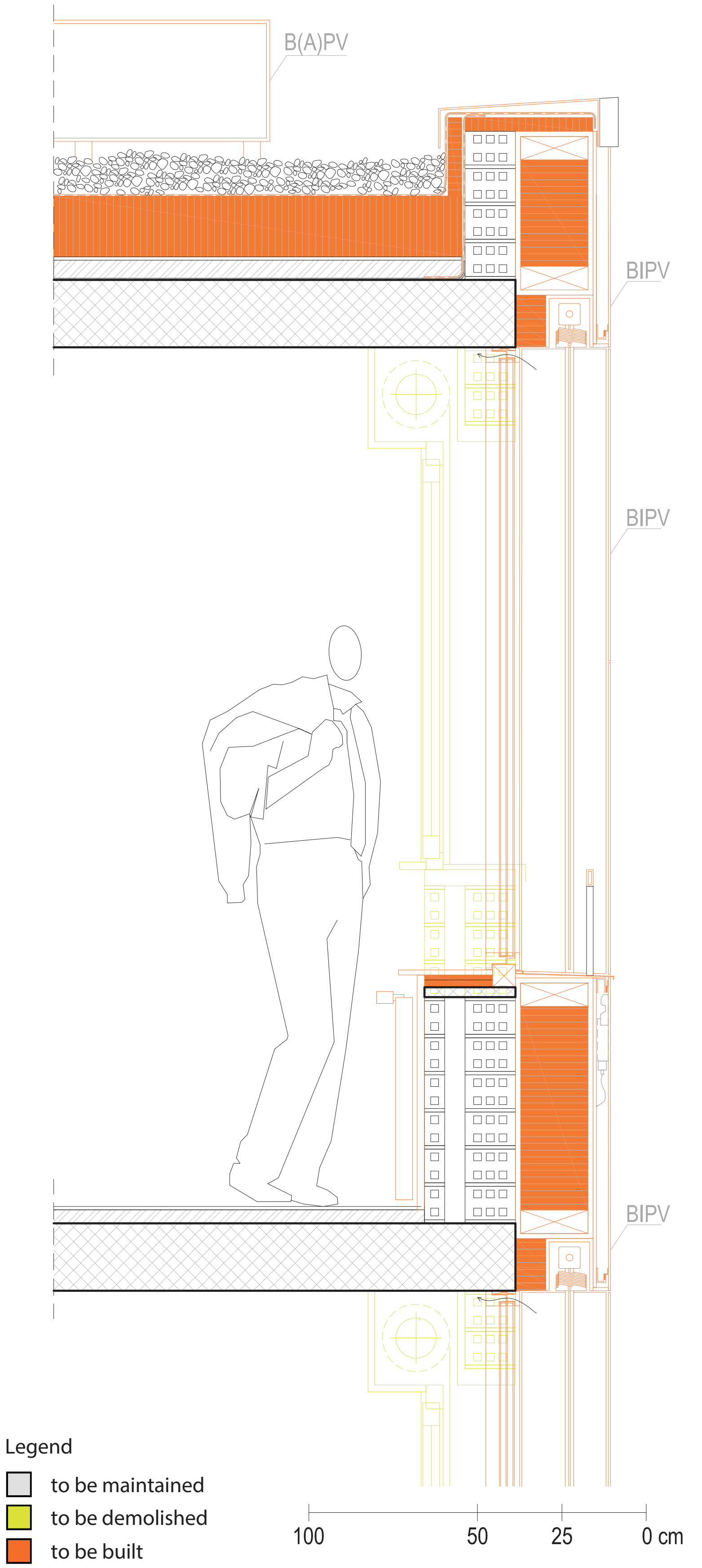


Figure 6-43. Façade constructive detail, **S3 – BIPV Transformation**, Archetype 3.

Roof: B(A)PV panels (east-west oriented), Gravel 5-10 cm, Bitumen 0.4 cm, EPS extruded polystyrene 22 cm, Reinforced concrete slab 20 cm, Bitumen 0.4 cm.

Façade: Custom-size PV panels, Light grey coloured film with η-11% (STC), Air gap 5 cm, Wood particle board 1.5 cm, EPS expanded polystyrene 19 cm, Wood particle board 1.5 cm, Ceramic brick 15 cm, Air gap 6 cm, Ceramic brick 6 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 5cm, Cement screed 3 cm, Reinforced concrete slab 20 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

External floor (ground): Ceramic floor tiles 2 cm, Cement screed 7 cm, Reinforced concrete slab 20 cm, XPS extruded polystyrene 4 cm.

Solar protections: Wooden roller shutter 3cm.

Balconies: Reinforced concrete slab 20 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

Potentially active surfaces

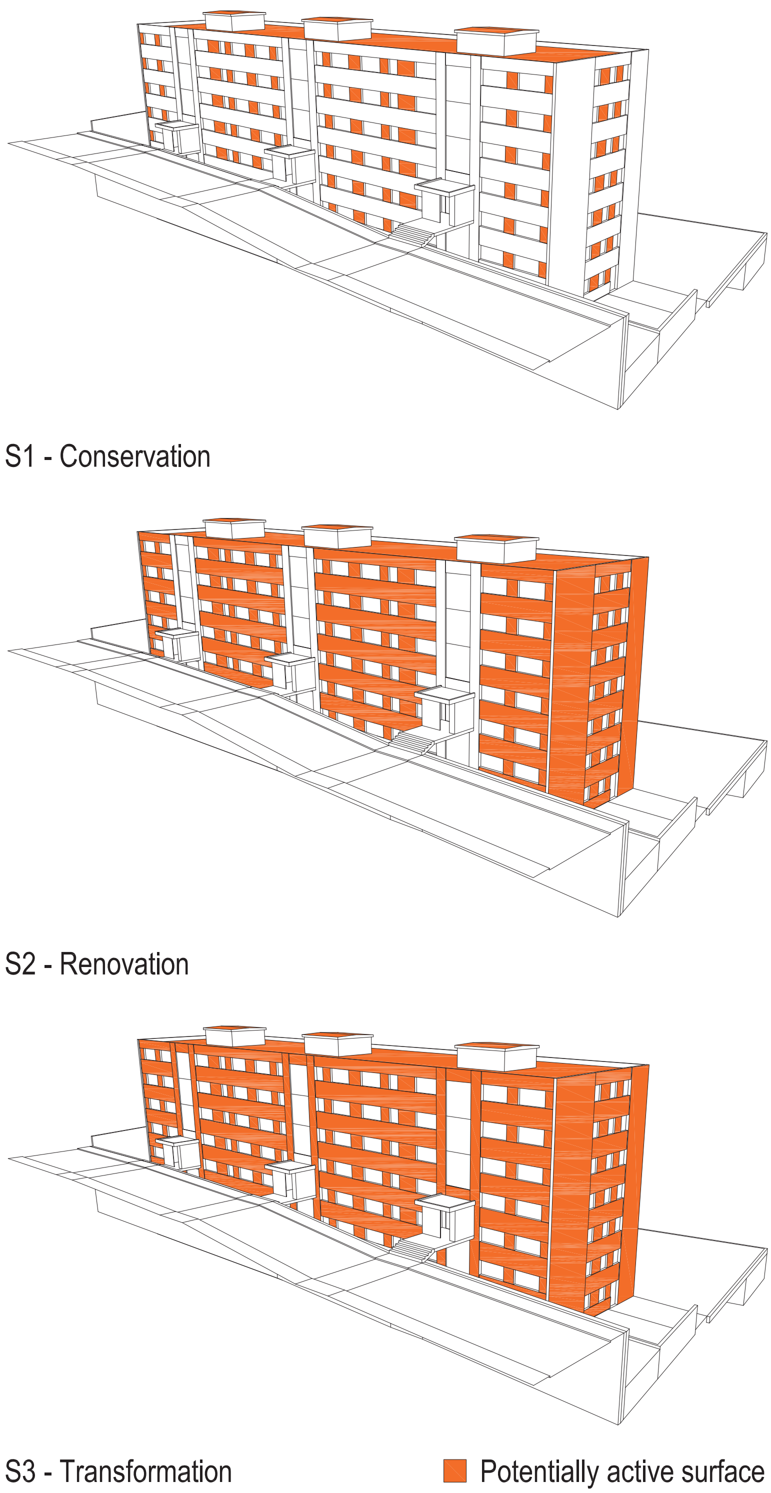


Figure 6-44. Potentially active surfaces detected for the different BIPV design scenarios, Archetype 3. Surfaces and equivalent power S1 (462 m^2 – 79 kWp), S2 (1'526 m^2 – 262 kWp), S3 (1'845 m^2 – 316 kWp).

Building envelope characteristics

S0 – Baseline	U-value
Roof – *ref. Ds02**	**U-0.25 W/m²·K**
Façade – *ref. Ws11**	**U-0.25 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-0.60 W/m²·K**
Openings **	**U-1.30 W/m²·K**
Airtightness | Infiltration rate	*1.00 ACH*
S1 – BIPV Conservation	
Roof – *ref. Ds02**	**U-0.20 W/m²·K**
Façade – *ref. Ws11**	**U-0.20 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-0.60 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.70 ACH*
S2 – BIPV Renovation	
Roof – *ref. Ds02**	**U-0.19 W/m²·K**
Façade – *ref. Ws11**	**U-0.19 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-0.60 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.50 ACH*
S3 – BIPV Transformation	
Roof – *ref. Ds02**	**U-0.17 W/m²·K**
Façade – *ref. Ws11**	**U-0.17 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-0.60 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.50 ACH*

Table 6-9. Final U-value of the different parts of the building envelope for each design scenario (E0, S0, S1, S2 and S3) for Archetype 3. Layers composition and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.5.

Thermal bridge analysis

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	+0.04	+0.04	+0.04	+0.04
TB2	+0.09	+0.10	+0.10	+0.07
TB3	+0.14	+0.13	+0.13	+0.11
TB4	+0.71	+0.68	+0.68	+0.63
TB6	+0.68	+0.66	+0.66	+0.62
TB7	-	-	-	+0.25
TB8	+0.10	+0.14	+0.14	+0.15
TB9	+0.15	+0.11	+0.11	+0.12
TB10	+0.11	+0.15	+0.15	+0.16
TB11	-	-	-	ΔU +0.03 W/m²·K

All values are adopted from the Swiss catalogue of thermal bridges [Infomind Sàrl 2003].

Table 6-10. Linear thermal bridges values for Archetype 3. Detailed information in Annexe 10.1.5.

Requirements comparison

Archetype 3	Oil / Gas boiler				Heat-Pump		
Requirements	S0	S1	S2	S3	S1	S2	S3
SIA 380/1:2016	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie® 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-P 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-A 2017 Renovation	*NO*	*NO*	*NO*	**YES**	*NO*	**YES**	**YES**
2'000-watt society	*NO*	*NO*	*NO*	**YES**	**YES**	**YES**	**YES**
Construction	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
Exploitation	*NO*	*NO*	*NO*	*YES*	*YES*	*YES*	*YES*
PV > 10 Wp/m² of ERA	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

Table 6-11. Compliance check with energy requirements for Archetype 3.

6.4.4. Archetype 4

S0-Baseline | Archetype 4

Figure 6-45. Computer-generated image of scenario S0-Baseline, Archetype 4.

For the **S0-Baseline** scenario of this archetype (Figure 6-45, Figure 6-46 and Figure 6-47), the strategies adopted correspond to:

- Internal insulation system maintaining the aspect of the building.
- Replacement of existing windows and roller blinds.

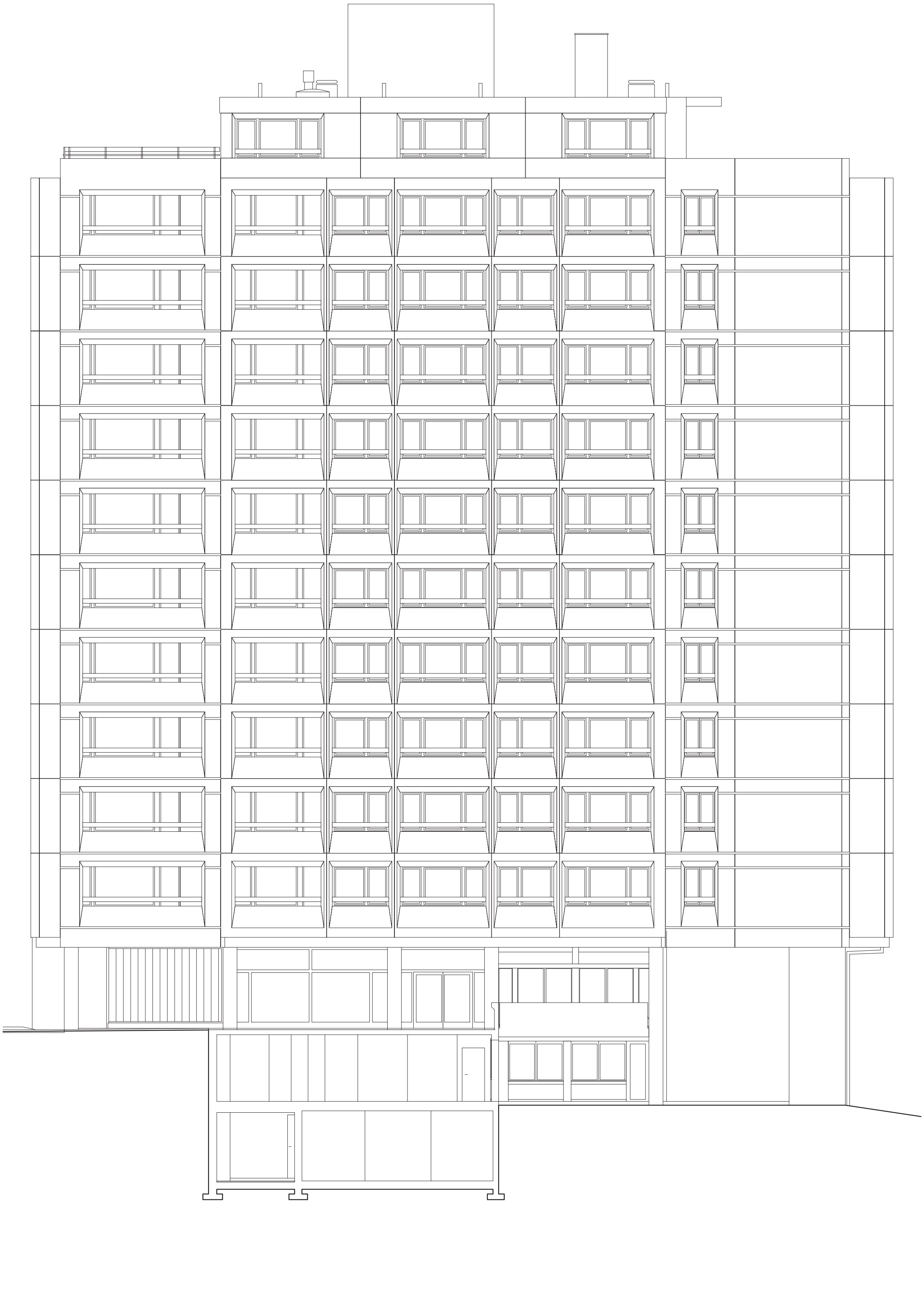


Figure 6-46. Design scenario S0-Baseline, Archetype 4.

Figure 6-47. Façade constructive detail, **S0 - Baseline**, Archetype 4.

Roof: Gravel 5 cm, Bitumen 0.4 cm, EPS extruded polystyrene 12 cm, Cement screed 4 cm, Bitumen 0.4 cm, Reinforced concrete slab 22 cm, Gypsum plaster 1 cm.

Façade: Reinforced concrete 2-14 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 14 cm, Mineral wool insulation 10 cm, Vapour barrier, Plasterboard 1.5 cm.

Internal floor (against non-heated space): Linoleum floor 0.5 cm, Cement screed 5 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

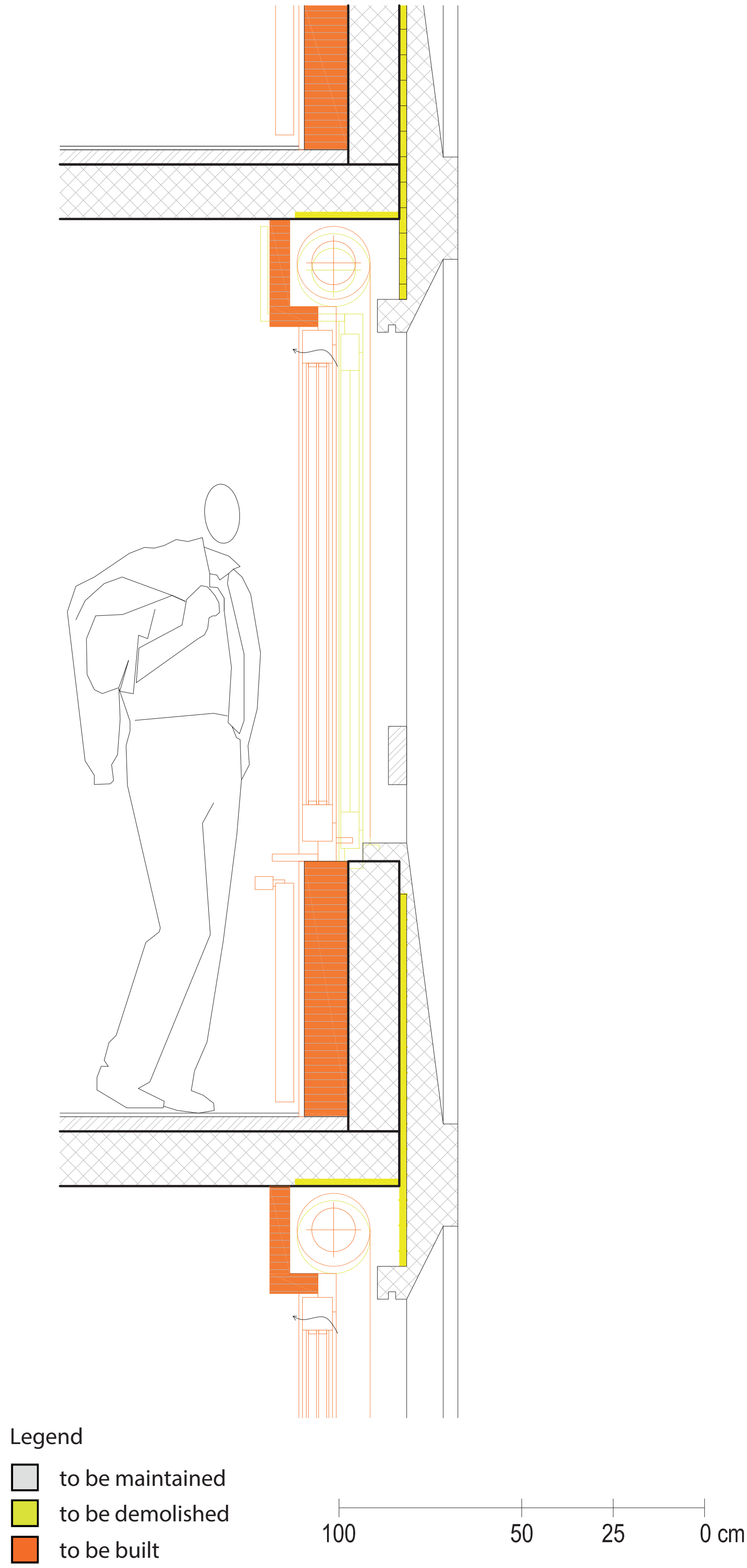
External floor (ground): Ceramic floor tiles 1 cm, Cement screed 6 cm, Reinforced concrete slab 22 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Reinforced concrete slab 22 cm.

Openings: PVC frame windows with double-glazing 4-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)



S1-Conservation | Archetype 4

Figure 6-48. Computer-generated image of scenario S1-Conservation, Archetype 4.

For the **S1–BIPV conservation** scenario (Figure 6-48, Figure 6-49 and Figure 6-50), in addition to the interventions of S0-Baseline, we propose to cover the roof using south-oriented BAPV panels and the railing of the windows using coloured custom-size BIPV elements, in order to maintain the building's expression. The added strategies are:

- BAPV elements on the flat roof (134 m^2):
  - South-oriented PV panels with mono-Si cells technology (with an efficiency of 20% in STC).
  - Standard size modules.

- BIPV elements in façade (windows railings) (431 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3800 mm, width 50-2400 mm) using 6″ standard size solar cells **[metsolar 2018b]** minimising visible joints.
  - Visual customisation using concrete coloured film.
  - Final performance estimation of about 13% in STC.

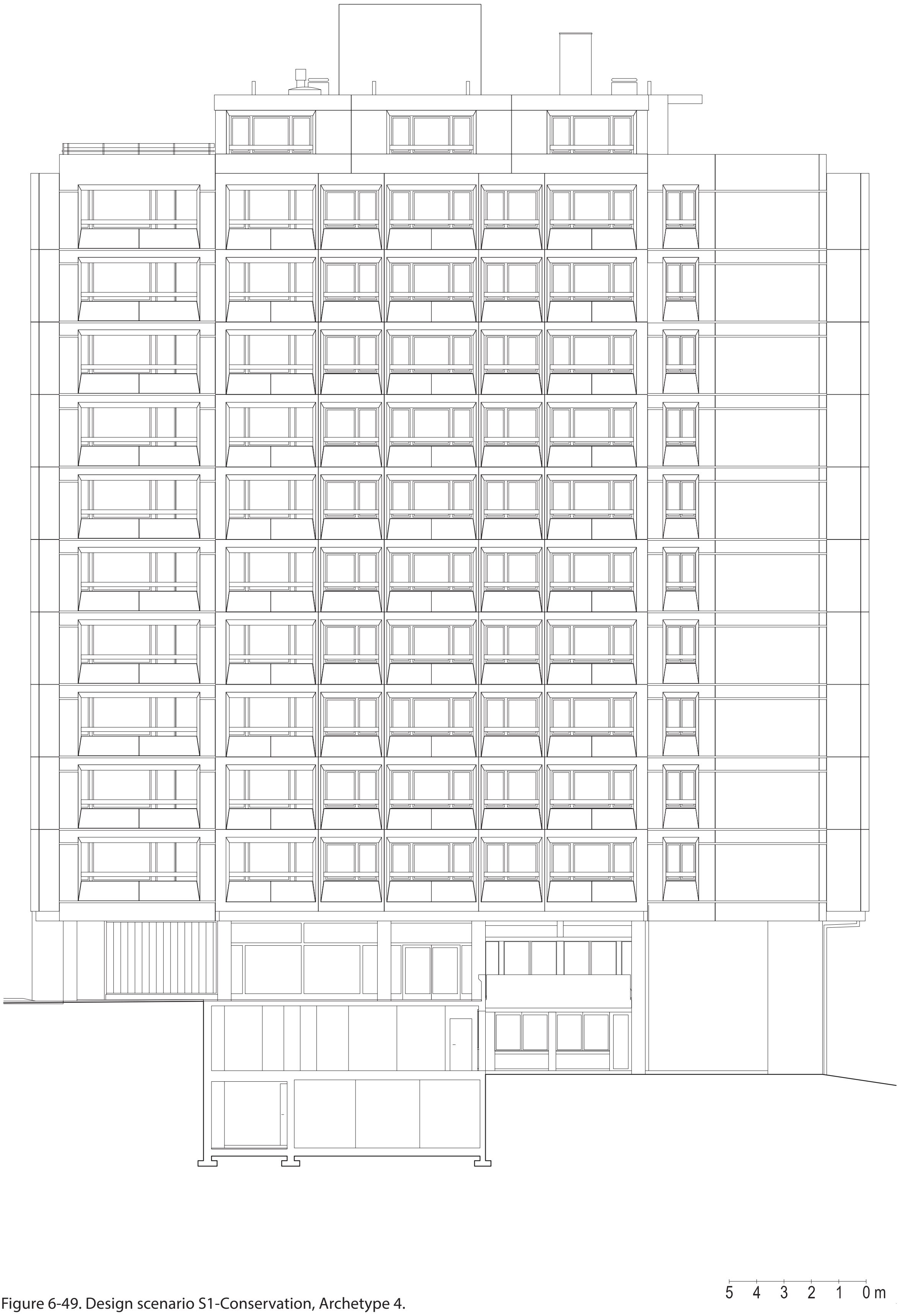


Figure 6-49. Design scenario S1-Conservation, Archetype 4.

Figure 6-50. Façade constructive detail, **S1-Conservation,** Archetype 4.

Roof: B(A)PV panels (south-oriented), Gravel 5 cm, Bitumen 0.4 cm, EPS extruded polystyrene 15 cm, Cement screed 4 cm, Bitumen 0.4 cm, Reinforced concrete slab 22 cm, Gypsum plaster 1 cm.

Façade: Reinforced concrete 2-14 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 14 cm, Mineral wool insulation 14 cm, Vapour barrier, Plasterboard 1.5 cm.

On windows railings: Custom-size PV panels, dark grey coloured film with η-13% (STC), Air gap 5 cm.

Internal floor (against non-heated space): Linoleum floor 0.5 cm, Cement screed 5 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

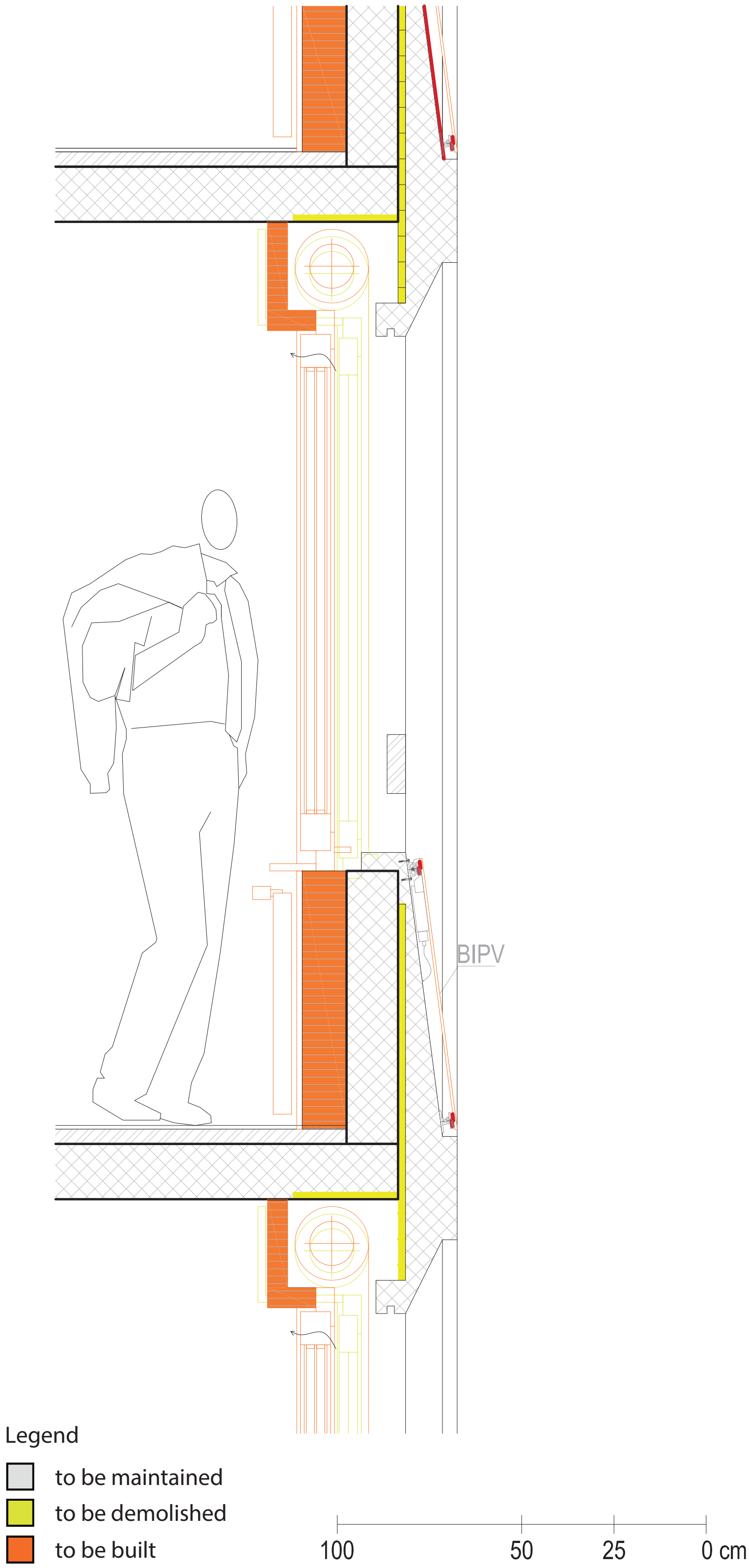
External floor (ground): Ceramic floor tiles 1 cm, Cement screed 6 cm, Reinforced concrete slab 22 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Reinforced concrete slab 22 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)



S2-Renovation | Archetype 4

Figure 6-51. Computer-generated image of scenario S2-Renovation, Archetype 4.

For the **S2–BIPV renovation** scenario (Figure 6-51, Figure 6-52 and Figure 6-53), a ventilated façade system with external insulation is implemented, including the replacement of existing windows, covering the roof with standard south-oriented BAPV panels, and placing BIPV elements on the railing of windows and the largest opaque surfaces of the rest of the façade, while maintaining the main lines of the building's expression. The strategies adopted correspond to:

- Ventilated façade system with external thermal insulation, reproducing the general lines of the existing façade.
- Replacement of windows and roller blinds.
- BAPV elements on the flat roof (134 m^2):
  - South-oriented PV panels with mono-Si cells technology (with an efficiency of 20% in STC).
  - Standard size modules.

- BIPV elements in façade (windows railings) (431 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3800 mm, width 50-2400 mm) using 6″ standard size solar cells **[metsolar 2018b]**.
  - Visual customisation using dark concrete coloured film.
  - Final performance estimation of about 13% in STC.
- BIPV elements in façade (the rest of the façade) (631 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Prioritising standard size according to Megaslate® system but with the possibility to use bigger panels respecting manufacturers recommendations for glass/glass modules (length 50-3’800 mm, width 50-2’400 mm) using 6″ standard size solar cells **[metsolar 2018a]** and minimising the variety of dimensions to simplify the electric connections.
  - Visual customisation using concrete coloured film.
  - Final performance estimation of about 13% in STC.

Figure 6-52. Design scenario S2-Renovation, Archetype 4.

Figure 6-53. Façade constructive detail, **S2-Renovation**, Archetype 4.

Roof: B(A)PV panels (south-oriented), Gravel 5 cm, Bitumen 0.4 cm, EPS extruded polystyrene 16 cm, Cement screed 4 cm, Bitumen 0.4 cm, Reinforced concrete slab 22 cm, Gypsum plaster 1 cm.

Façade: Custom-size PV panels, Light / dark grey coloured film with η-11-13% (STC), Air gap 5 cm, Wood particle board 1.5 cm, EPS expanded polystyrene 14 cm, Reinforced concrete 2-14 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 14 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Linoleum floor 0.5 cm, Cement screed 5 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

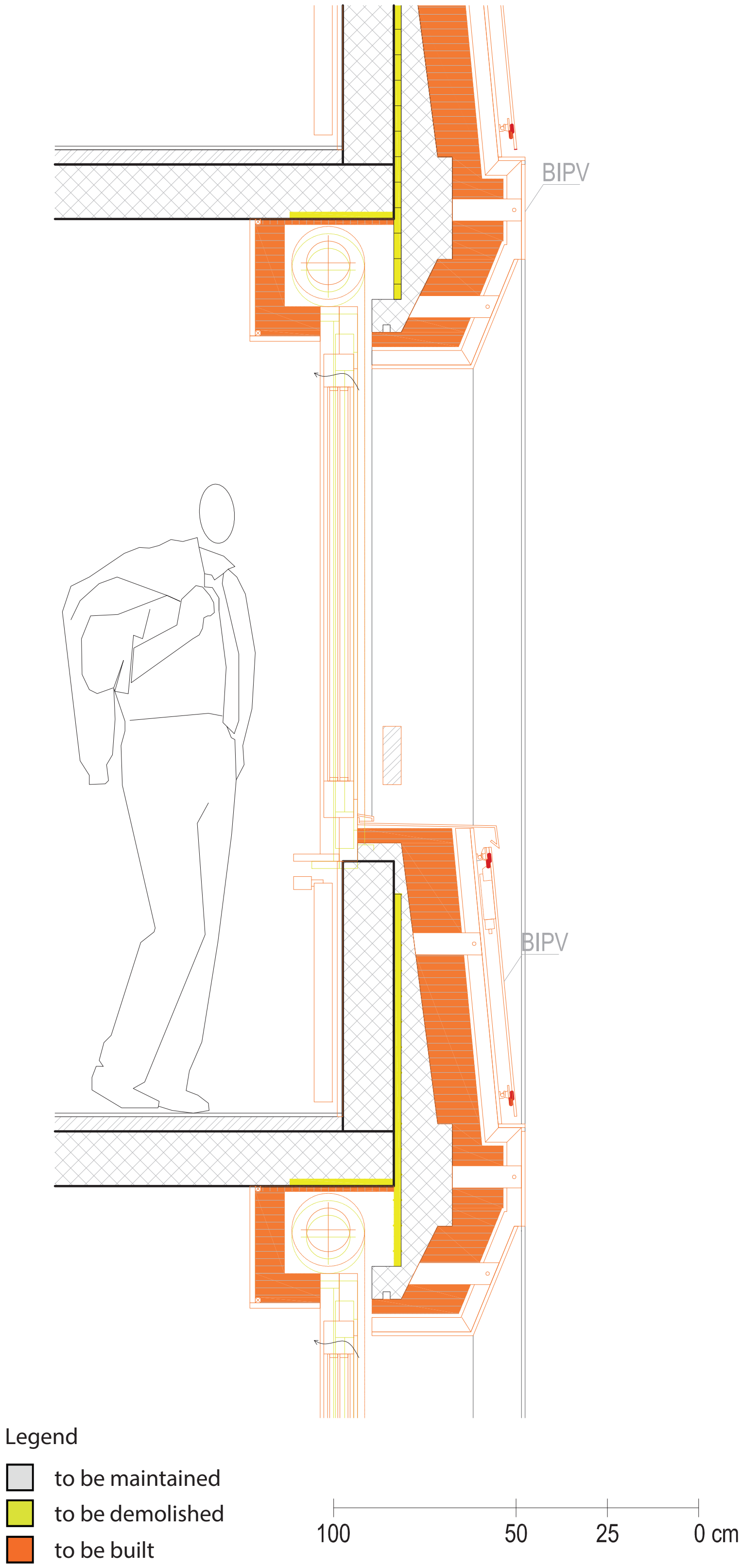
External floor (ground): Ceramic floor tiles 1 cm, Cement screed 6 cm, Reinforced concrete slab 22 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Reinforced concrete slab 22 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)



S3-Transformation | Archetype 4

Figure 6-54. Computer-generated image of scenario S3-Transformation, Archetype 4.

Finally, for the **S3–BIPV transformation** scenario (Figure 6-54, Figure 6-55 and Figure 6-56), a prefabricated wooden structure façade to plug-in directly on the existing façade is implemented, which includes external insulation (ventilated façade), new windows and BIPV elements covering all opaque surfaces. The strategies adopted correspond to:

- Timber frame prefabricated ventilated façade system including all the envelope components and modulated according to the standard size of BIPV elements, prioritising low-carbon materials. Part of the existing window railing is demolished to enlarge the openings in order to provide more daylight and outdoor view to the apartments.

- BAPV elements on the flat roof (134 m^2):
  - Double-oriented (east-west) PV panels with mono-Si cells technology (with an efficiency of 20% in STC).
  - Standard size modules.
- BIPV elements in façade (2’058 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3’800 mm, width 50-2’400 mm) using 6” standard size solar cells **[metsolar 2018a]** and minimising the variety of dimensions to simplify the electric connections.
  - Visual customisation using dark grey coloured film.
  - Final performance estimation of about 14.5% in STC.

Figure 6-55. Design scenario S3-Transformation, Archetype 4.

Figure 6-56. Façade constructive detail, **S3-Transformation**, Archetype 4.

Roof: B(A)PV panels (south-oriented), Gravel 5 cm, Bitumen 0.4 cm, EPS extruded polystyrene 18 cm, Cement screed 4 cm, Bitumen 0.4 cm, Reinforced concrete slab 22 cm, Gypsum plaster 1 cm.

Façade: Custom-size PV panels, Light / dark grey coloured film with η-11-13% (STC), Air gap 5 cm, Wood particle board 1.5 cm, EPS expanded polystyrene 18 cm, Wood particle board 1.5 cm, Reinforced concrete 14 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Linoleum floor 0.5 cm, Cement screed 5 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Synthetic plaster 1 cm.

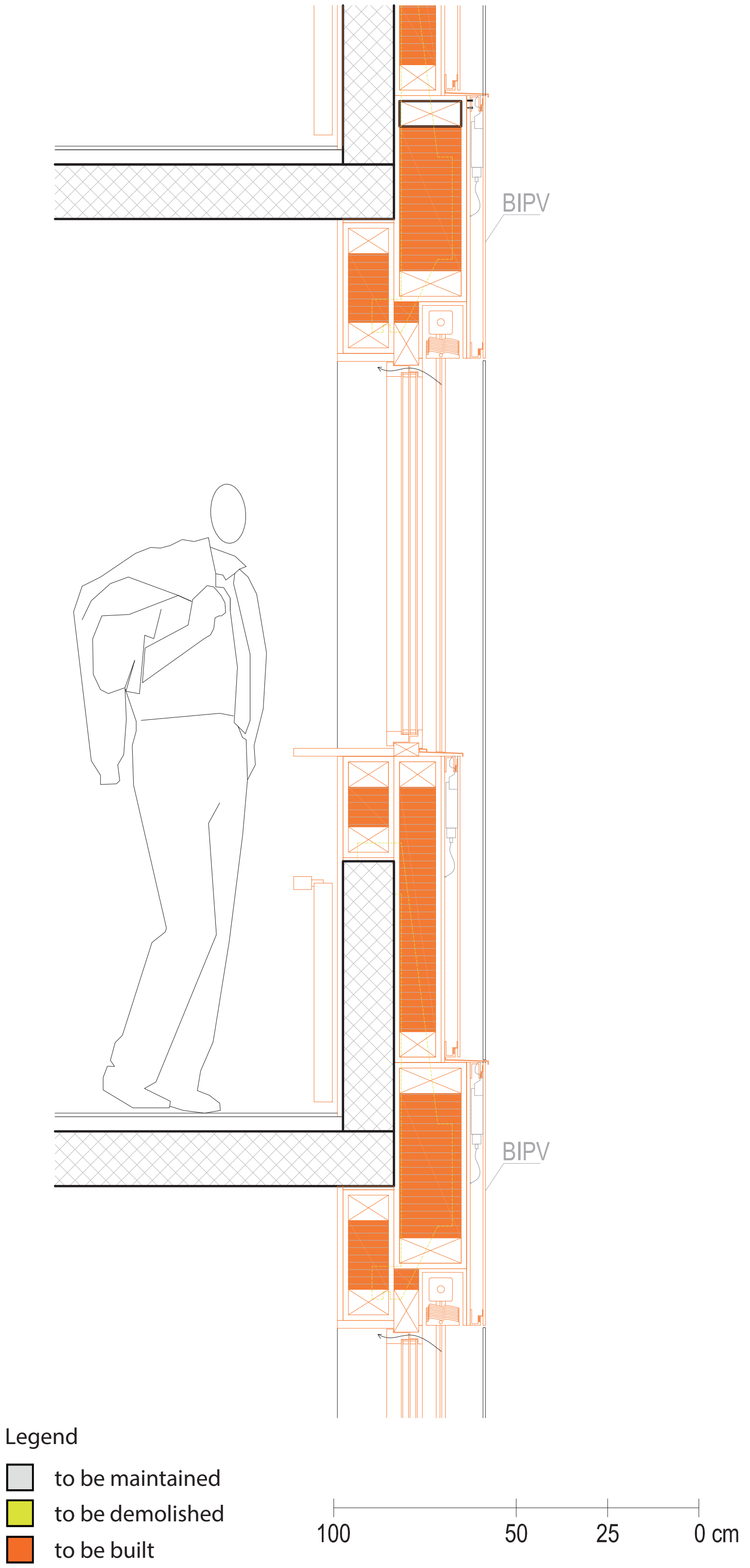
External floor (ground): Ceramic floor tiles 1 cm, Cement screed 6 cm, Reinforced concrete slab 22 cm.

Solar protections: Wooden roller shutter 3 cm.

Balconies: Reinforced concrete slab 22 cm.

Openings: Wooden frame windows with triple-glazing 4-12(argon)-6-12(argon)-4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)



Potentially active surfaces

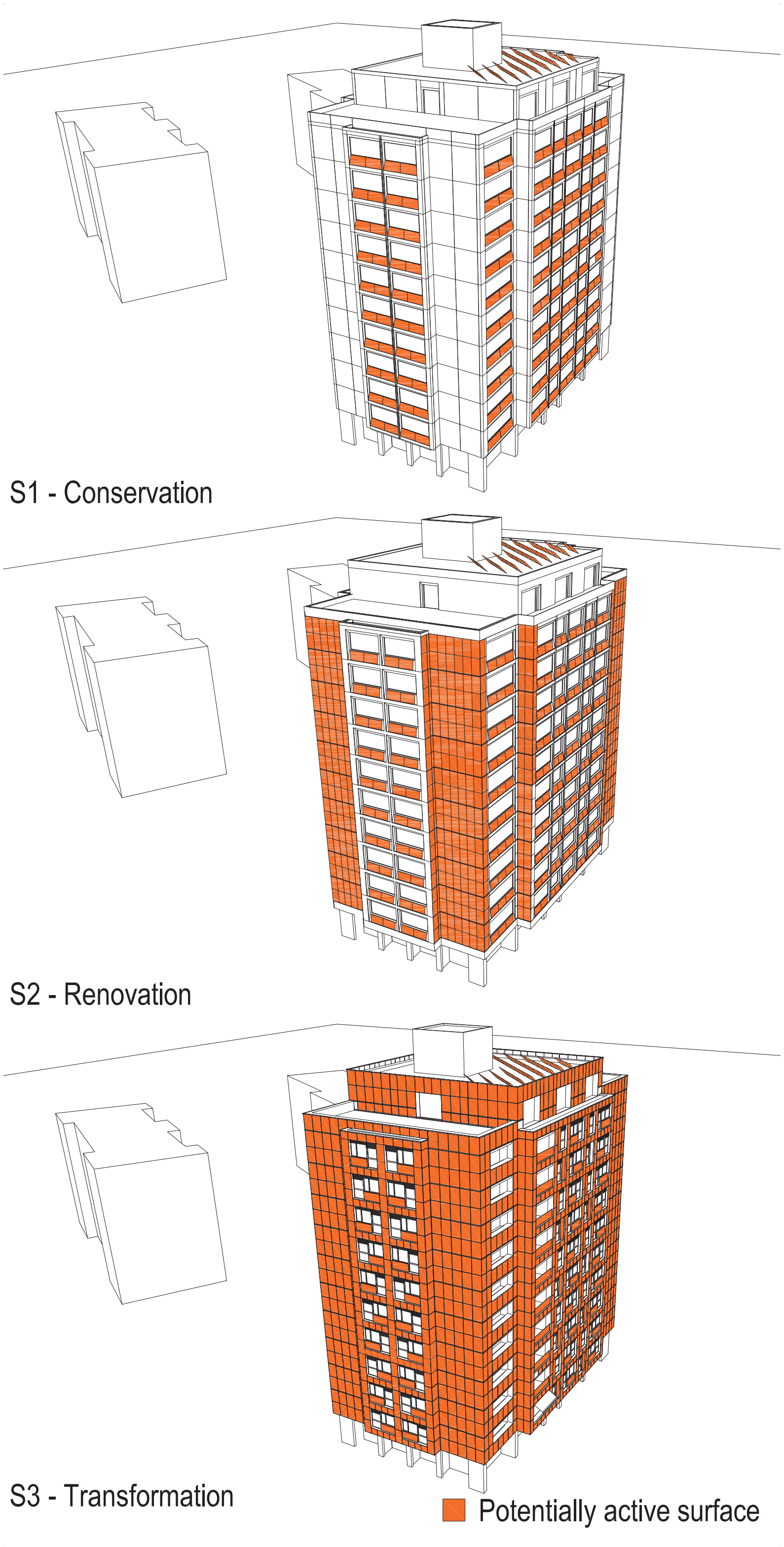


Figure 6-57. Potentially active surfaces detected for the different BIPV design scenarios, Archetype 4. Surfaces and equivalent power S1 (565 m² – 97 kWp), S2 (1'196 m² – 205 kWp), S3 (2'192 m² – 376 kWp).

Building envelope characteristics

Table 6-12. Final U-value of the different parts of the building envelope for each design scenario (E0, S0, S1, S2 and S3) for Archetype 4. Layers composition and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.6.

S0 – Baseline	U-value
Roof – *ref. Ds02**	**U-0.25 W/m²·K**
Façade – *ref. Ws11**	**U-0.25W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.44 W/m²·K**
Openings **	**U-1.30 W/m²·K**
Airtightness | Infiltration rate	*1.50 ACH*
S1 – BIPV Conservation	
Roof – *ref. Ds02**	**U-0.20 W/m²·K**
Façade – *ref. Ws11**	**U-0.20 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.44 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*1.00 ACH*
S2 – BIPV Renovation	
Roof – *ref. Ds02**	**U-0.19 W/m²·K**
Façade – *ref. Ws11**	**U-0.19 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.44 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.70 ACH*
S3 – BIPV Transformation	
Roof – *ref. Ds02**	**U-0.17 W/m²·K**
Façade – *ref. Ws11**	**U-0.17 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.44 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.50 ACH*

Thermal bridge analysis

Table 6-13. Linear thermal bridges values for Archetype 4. Detailed information in Annexe 10.1.6.

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	+0.63	+0.61	+0.04	+0.04
TB2	-0.12	-0.08	+0.05	+0.07
TB3	+0.19	+0.17	+0.15	+0.15
TB4	+0.83	+0.78	+0.78	+0.71
TB6	+0.68	+0.66	+0.66	+0.62
TB7	-	-	-	+0.25
TB8	+0.06	+0.10	+0.14	+0.15
TB9	+0.09	+0.13	+0.11	+0.12
TB10	+0.11	+0.11	+0.15	+0.16
TB11	-	-	-	ΔU +0.03 W/m²·K

All values are adopted from the Swiss catalogue of thermal bridges [Infomind Sàrl 2003].

Requirements comparison

Table 6-14. Compliance check with energy requirements for Archetype 4.

Archetype 4	**Oil / Gas boiler**				**Heat-Pump**		
Requirements	S0	S1	S2	S3	S1	S2	S3
SIA 380/1:2016	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie® 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-P 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-A 2017 Renovation	*NO*	*NO*	*NO*	**YES**	*NO*	**YES**	**YES**
2'000-watt society	*NO*	*NO*	*NO*	*NO*	**YES**	**YES**	**YES**
Construction	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
Exploitation	*NO*	*NO*	*NO*	*NO*	*YES*	*YES*	*YES*
PV > 10 Wp/m² of ERA	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

6.4.5. Archetype 5

S0-Baseline | Archetype 5

Figure 6-58. Computer-generated image of scenario S0-Baseline, Archetype 5.

For the **S0-Baseline** scenario of this archetype (Figure 6-76 and 6-77), the strategies adopted correspond to:

- Internal insulation (roof and slab basement).
- Replacement of existing windows.

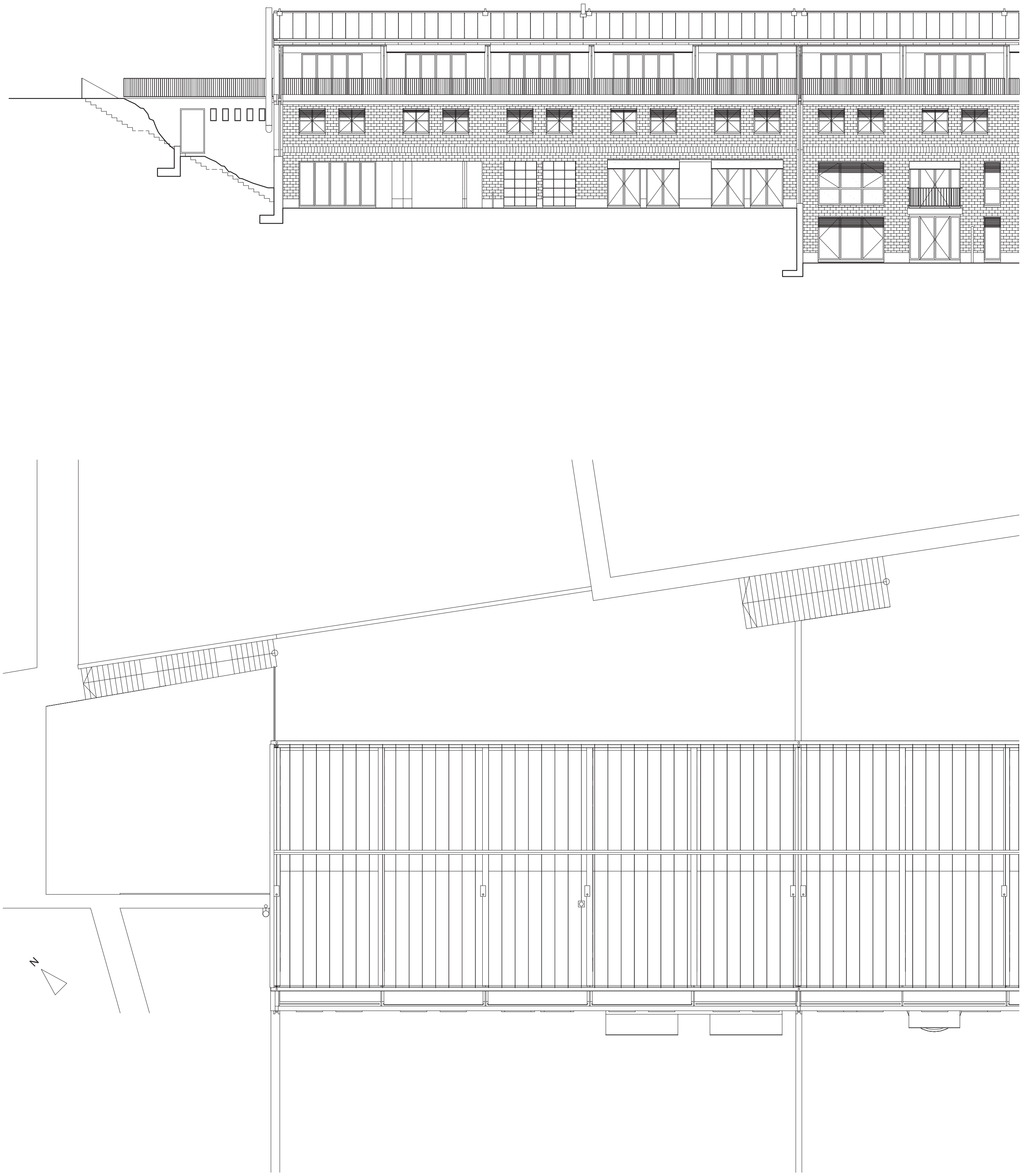
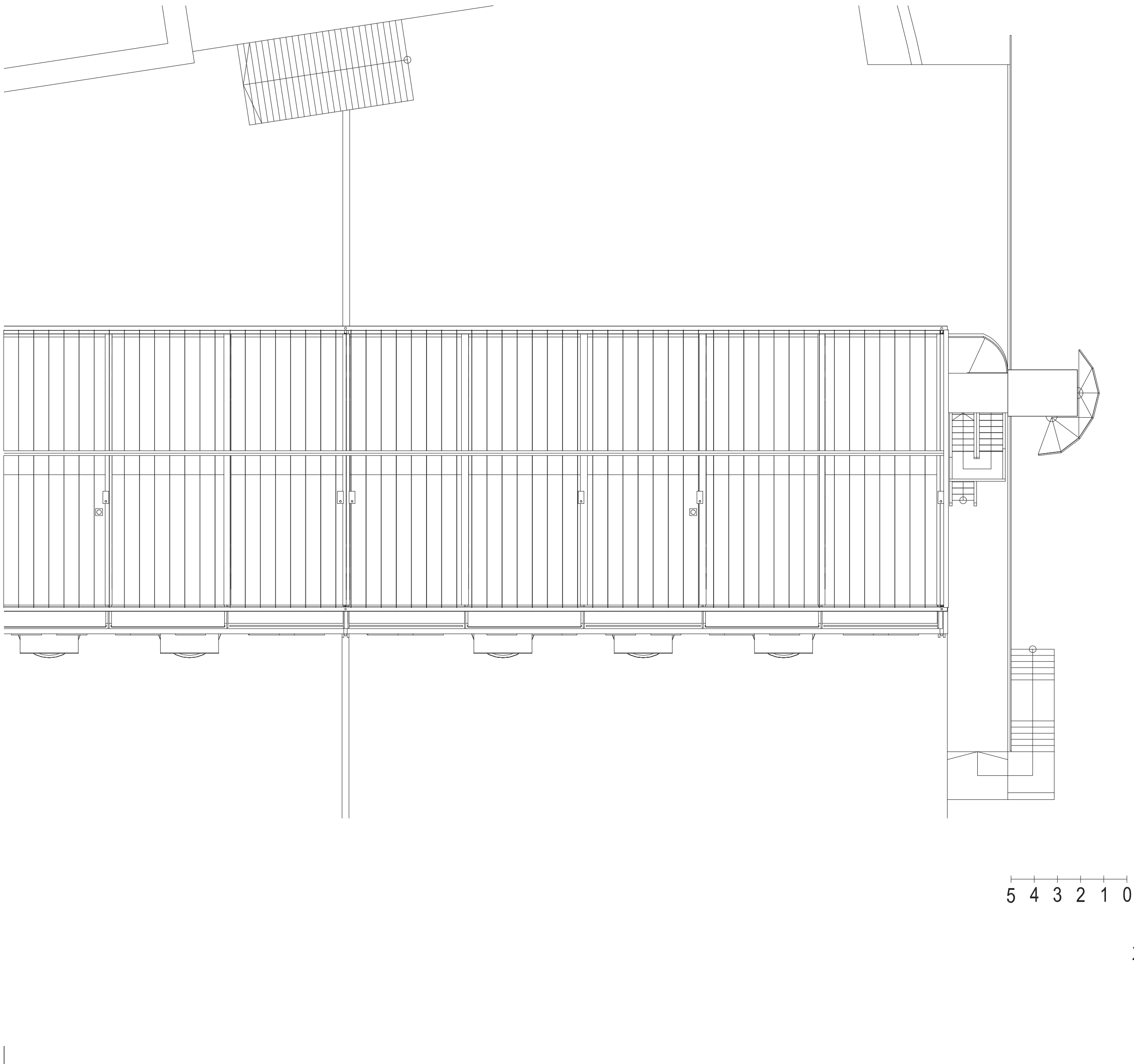


Figure 6-59. Design scenario S0-Baseline, Archetype 5.


5 4 3 2 1 0 m

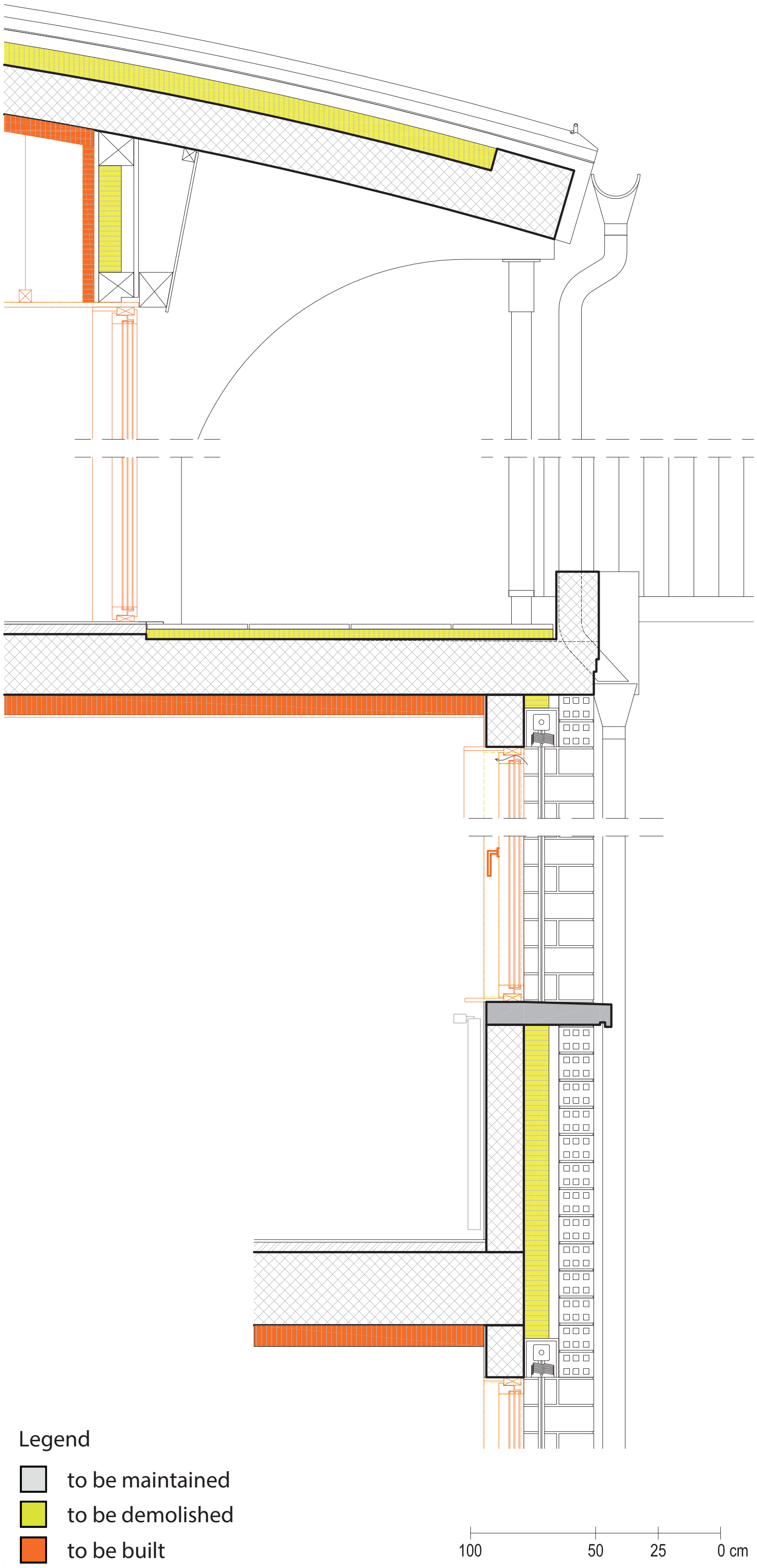


Figure 6-60. Façade constructive detail, **S0-Baseline**, Archetype 5.

Roof (curved): Zinc sheet 0.5 cm, Air gap 5 cm, Vapour barrier, EPS expanded polystyrene (old) 8 cm, Reinforced concrete slab 20 cm, EPS expanded polystyrene 8 cm, Plasterboard 1.5 cm.

Roof (flat): Concrete tiles 2 cm, XPS extruded polystyrene 4 cm, Bitumen 0..4 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Plasterboard 1.5 cm.

Façade: Ceramic brick 14 cm, Air gap 4 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 15 cm, Gypsum plaster 1 cm.

Internal floor (against non-heated space): Timber floor 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm, EPS expanded polystyrene 10 cm, Plasterboard 1.5 cm.

External floor (ground): Ceramic floor tiles 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm.

Solar protections: Exterior aluminium blinds 10 cm.

Balconies: Reinforced concrete slab 30 cm.

Openings: PVC frame windows with double-glazing 4+12(argon)+4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S1-Conservation | Archetype 5

Figure 6-61. Computer-generated image of scenario S1-Conservation, Archetype 5.

For the **S1–BIPV conservation** scenario (Figure 6-78 and 6-79), in addition to the S0 interventions, strategies correspond to:

- BIPV elements on the curved roof (941 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 21.5% in STC).
  - Standard size (black colour) according to ISSOL products for seam roofing model *"Cenit design – Joint-Debout"* **[ISSOL 2017]**.

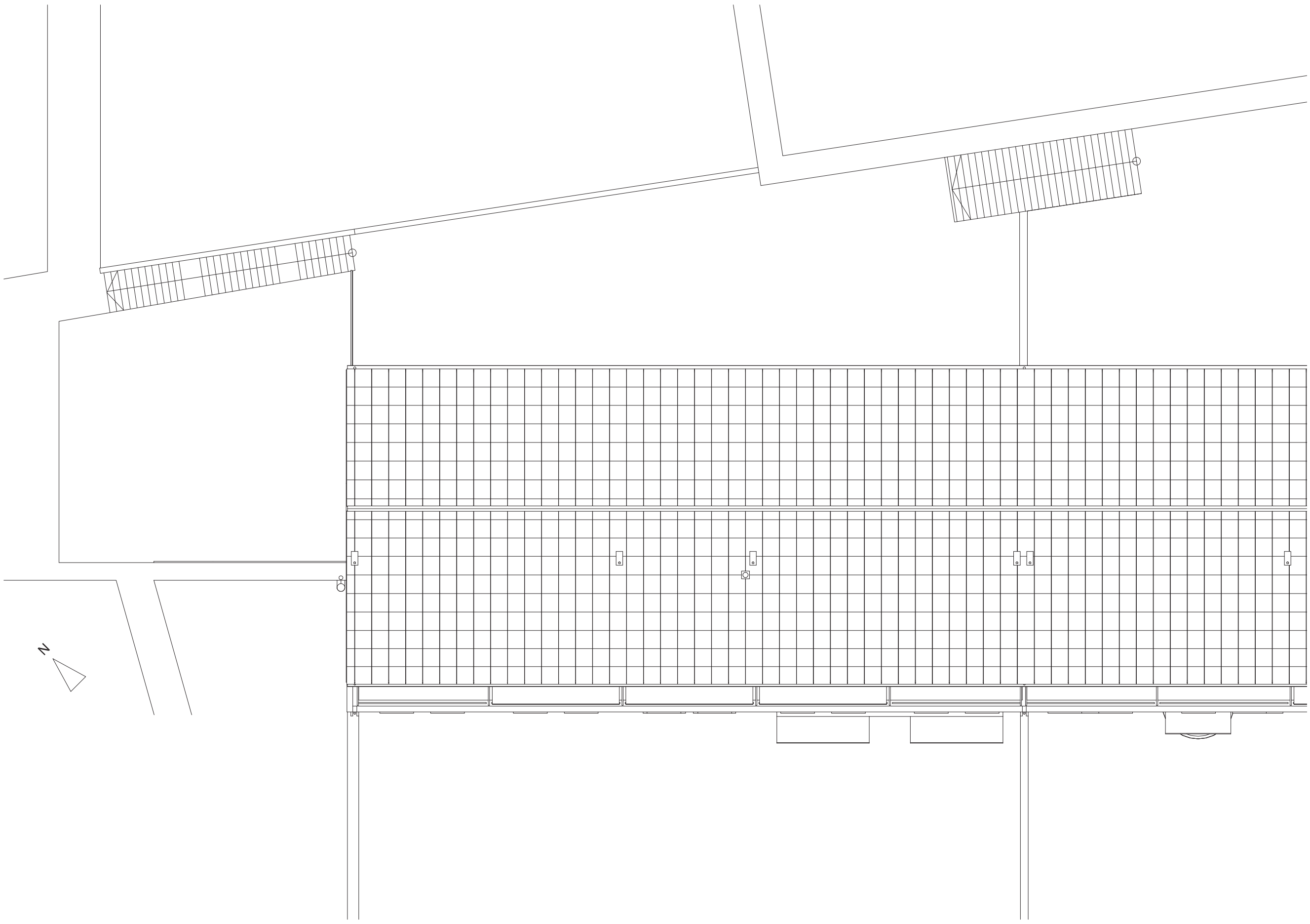
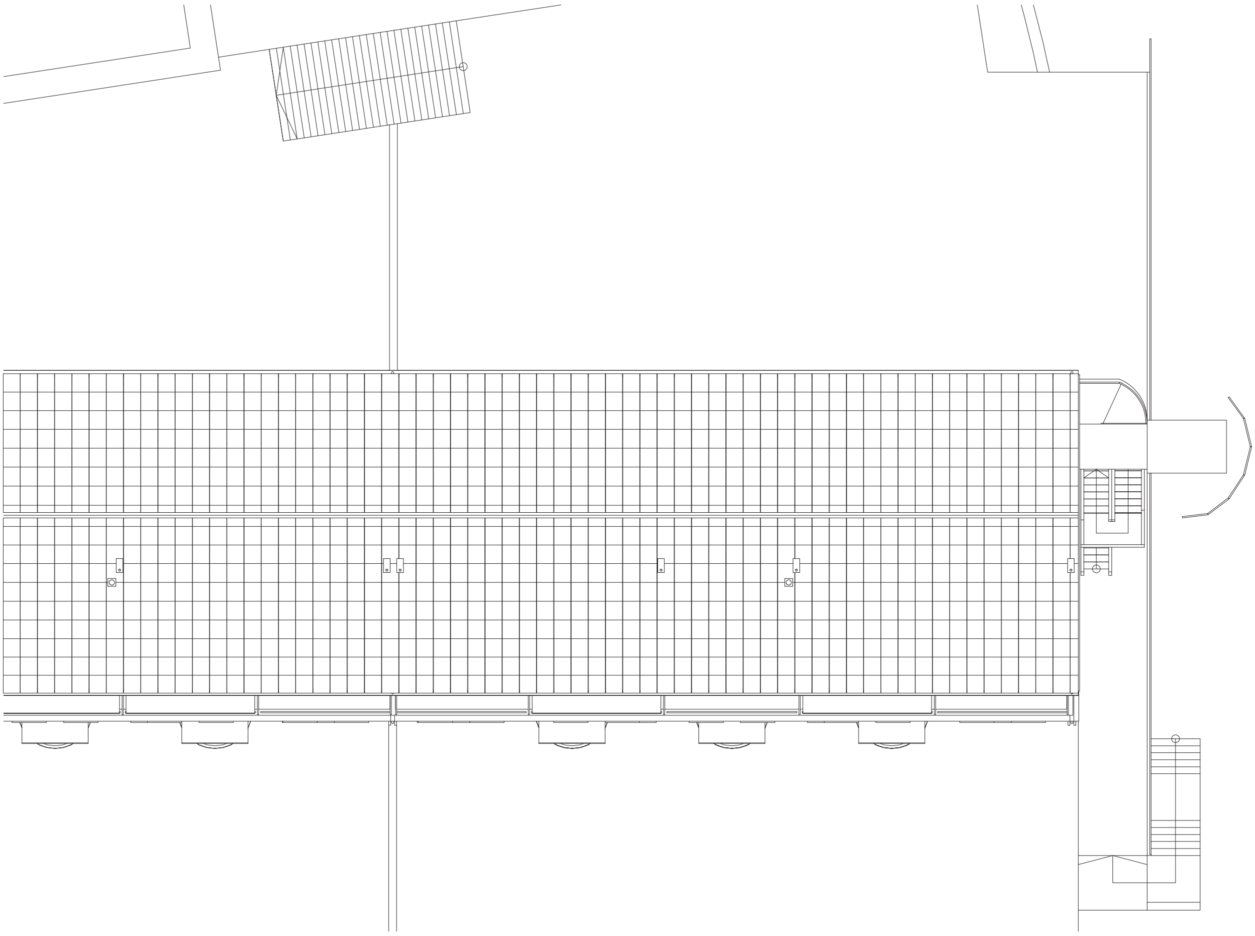
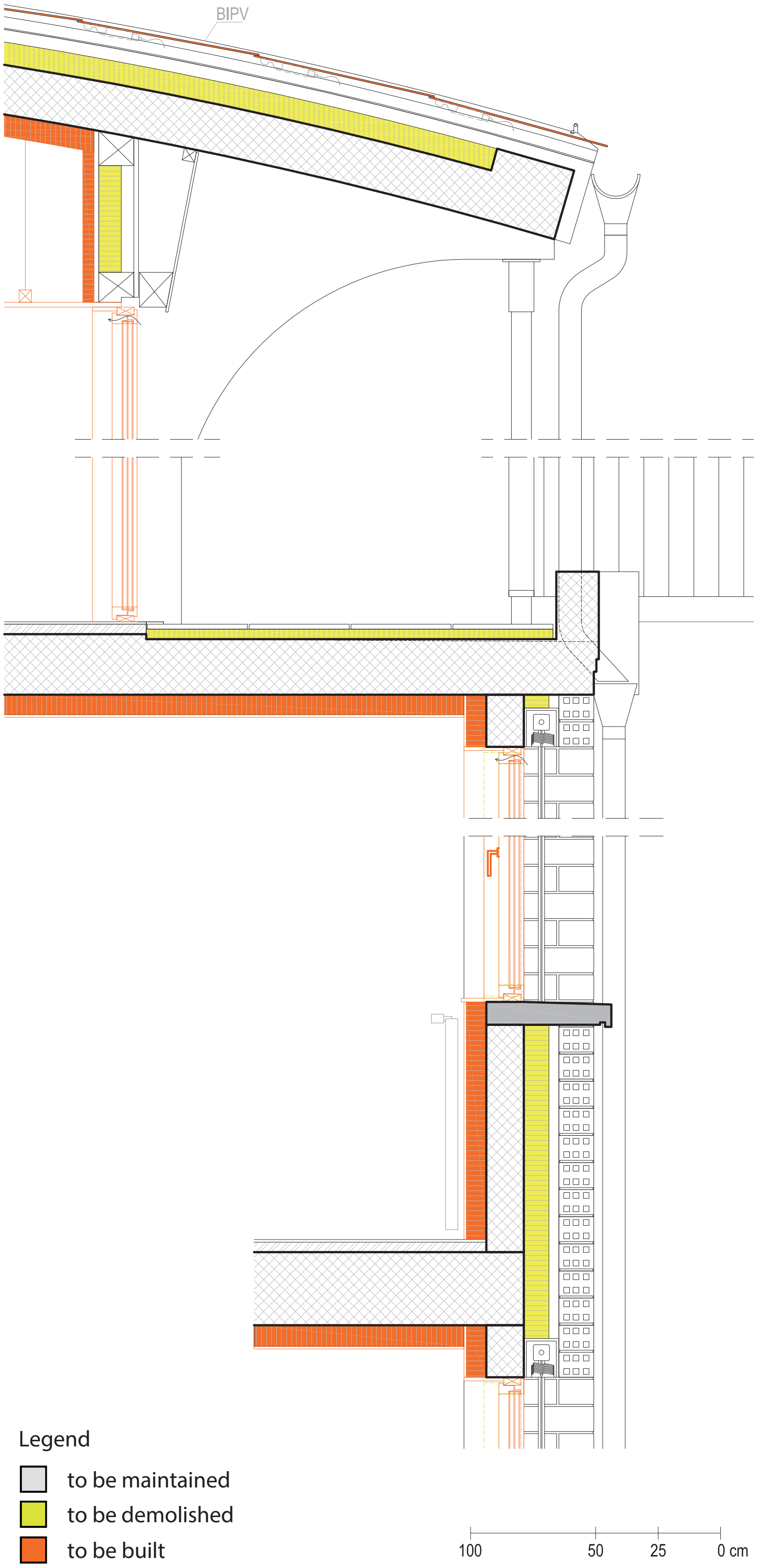


Figure 6-62. Design scenario S1-Conservation, Archetype 5.



5 4 3 2 1 0 m



Legend

to be maintained

to be demolished

to be built

Figure 6-63. Façade constructive detail, **S1-Conservation**, Archetype 5.

Roof (curved): Standard-size PV panels with η-21.5% (STC), Zinc sheet 0.5 cm, Air gap 5 cm, Vapour barrier, EPS expanded polystyrene (old) 8 cm, Reinforced concrete slab 20 cm, EPS expanded polystyrene 12 cm, Plasterboard 1.5 cm.

Roof (flat): Concrete tiles 2 cm, XPS extruded polystyrene 4 cm, Bitumen 0..4 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Vapour barrier, Plasterboard 1.5 cm.

Façade: Ceramic brick 14 cm, Air gap 4 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 15 cm, EPS expanded polystyrene 13 cm, Plasterboard 1.5 cm.

Internal floor (against non-heated space): Timber floor 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm, EPS expanded polystyrene 10 cm, Plasterboard 1.5 cm.

External floor (ground): Ceramic floor tiles 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm.

Solar protections: Exterior aluminium blinds 10 cm.

Balconies: Reinforced concrete slab 30 cm.

Openings: Wooden frame windows with triple-glazing 4+12(argon)+6 mm+12(argon)+4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S2-Renovation | Archetype 5

Figure 6-64. Computer-generated image of scenario S2-Renovation, Archetype 5.

For the **S2–BIPV renovation** scenario (Figure 6-80 and 6-81), the implemented strategies correspond to:

- Ventilated façade system with external thermal insulation, reproducing the general lines of the exiting façade (Eternit(R)).
- Replacement of windows and blinds.
- BIPV elements on the curved roof (941 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 21.5% in STC).
  - Standard size (black colour) according to ISSOL products for seam roofing model *"Cenit design – Joint-Debout"* **[ISSOL 2017]**.

- BIPV elements in façade (1’119 m²):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Custom-size BIPV elements, using a brick wall pattern.
  - Visual customisation using yellow coloured film.
  - Final performance estimation of about 11% in STC.
- BIPV elements on the balconies (attic floor) (140 m²):
  - Frameless PV panels with mono-Si cells technology.
  - Size customisation, adapted to the existing balconies.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.

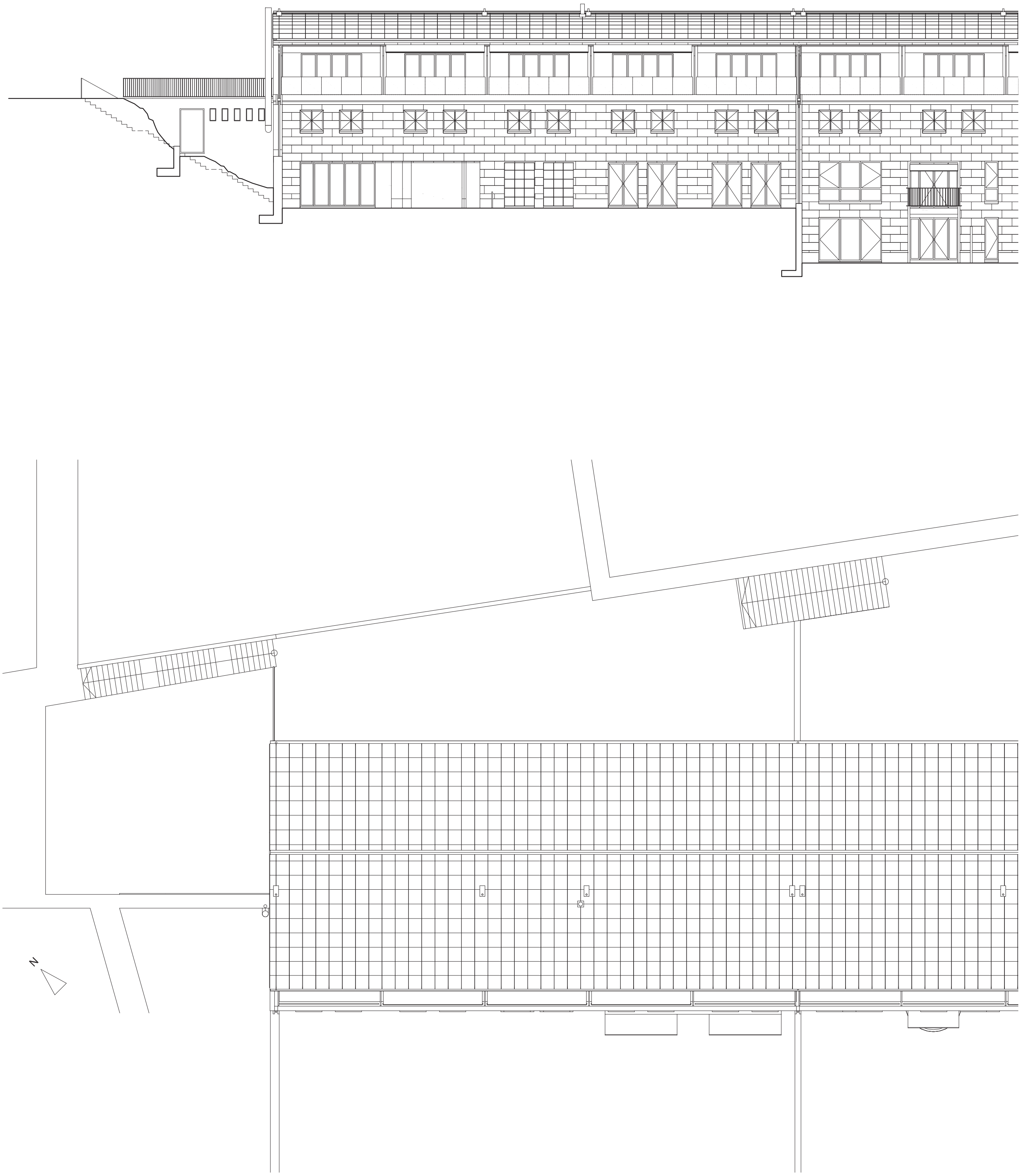
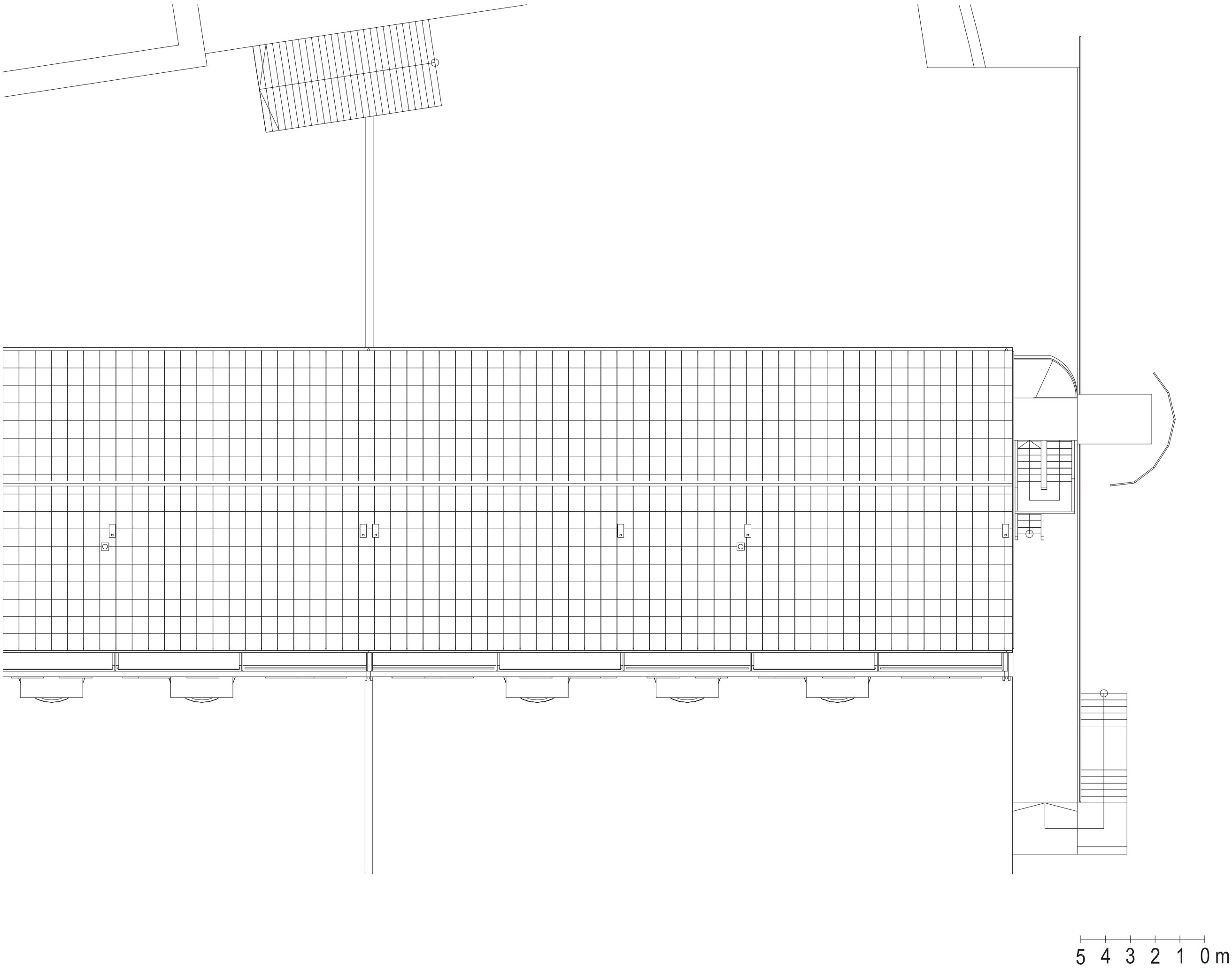


Figure 6-65. Design scenario S2-Renovation, Archetype 5.


5 4 3 2 1 0 m

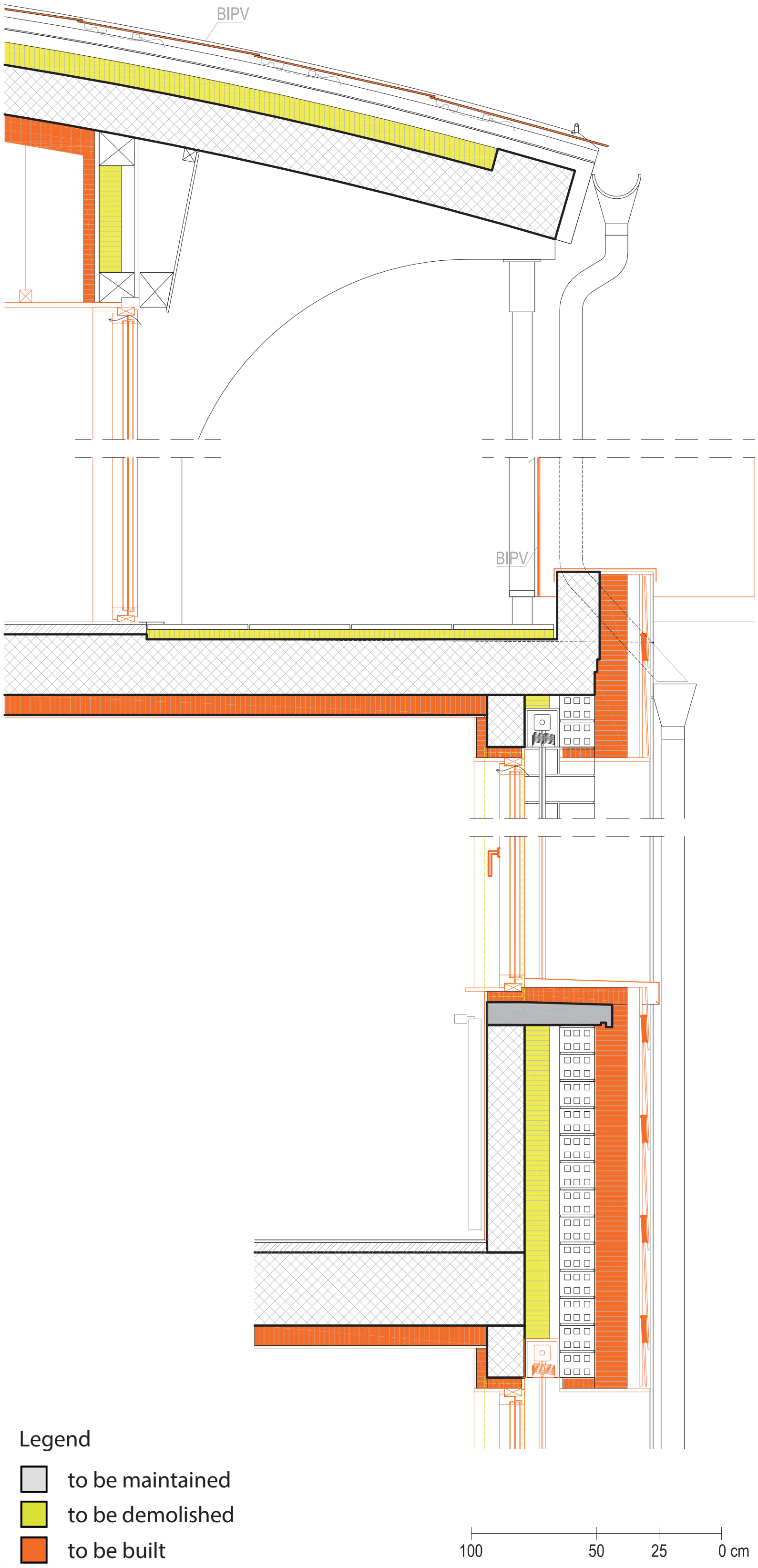


Figure 6-66. Façade constructive detail, **S2-Renovation**, Archetype 5.

Roof (curved): Standard-size PV panels with η-21.5% (STC), Zinc sheet 0.5 cm, Air gap 5 cm, Vapour barrier, EPS expanded polystyrene (old) 8 cm, Reinforced concrete slab 20 cm, EPS expanded polystyrene 13 cm, Plasterboard 1.5 cm.

Roof (flat): Concrete tiles 2 cm, XPS extruded polystyrene 4 cm, Bitumen 0..4 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Vapour barrier, Plasterboard 1.5 cm.

Façade: Custom-size PV panels, yellow coloured film with η-11% (STC), Air gap 5 cm, XPS extruded polystyrene 12 cm, Ceramic brick 14 cm, Air gap 4 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 15 cm, EPS expanded polystyrene 13 cm, Plasterboard 1.5 cm.

Internal floor (against non-heated space): Timber floor 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm, EPS expanded polystyrene 10 cm, Plasterboard 1.5 cm.

External floor (ground): Ceramic floor tiles 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm.

Solar protections: Exterior aluminium blinds 10 cm.

Balconies: Custom-size PV panels on railing, light grey coloured film with η-11% (STC), Reinforced concrete slab 30 cm.

Openings: Wooden frame windows with triple-glazing 4+12(argon)+6 mm+12(argon)+4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

S3-Transformation | Archetype 5

Figure 6-67. Computer-generated image of scenario S3-Transformation, Archetype 5.

Finally, for the **S3–BIPV transformation** scenario (Figure 6-82 and 6-83), the strategies are:

- Timber frame ventilated prefabricated façade system including all the envelope components, modulated according to the standard size of BIPV elements and prioritising low-carbon materials.
- BIPV elements on the curved roof (941 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 21.5% in STC).
  - Standard size (black colour) according to ISSOL products for seam roofing model *"Cenit design – Joint-Debout"* **[ISSOL 2017]**.

- BIPV elements in façade (1’119 m^2):
  - Frameless PV panels with mono-Si cells technology (with an efficiency of 18% in STC).
  - Size customisation respecting manufacturers recommendations for glass/glass modules (length 50-3’800 mm, width 50-2’400 mm) using 6” standard size solar cells **[metsolar 2018a]** and minimising the variety of dimensions to simplify the electric connections.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.
- BIPV elements on the balconies (attic floor) (140 m^2):
  - Frameless PV panels with mono-Si cells technology.
  - Size customisation, adapted to the existing balconies.
  - Visual customisation using light grey coloured film.
  - Final performance estimation of about 11% in STC.

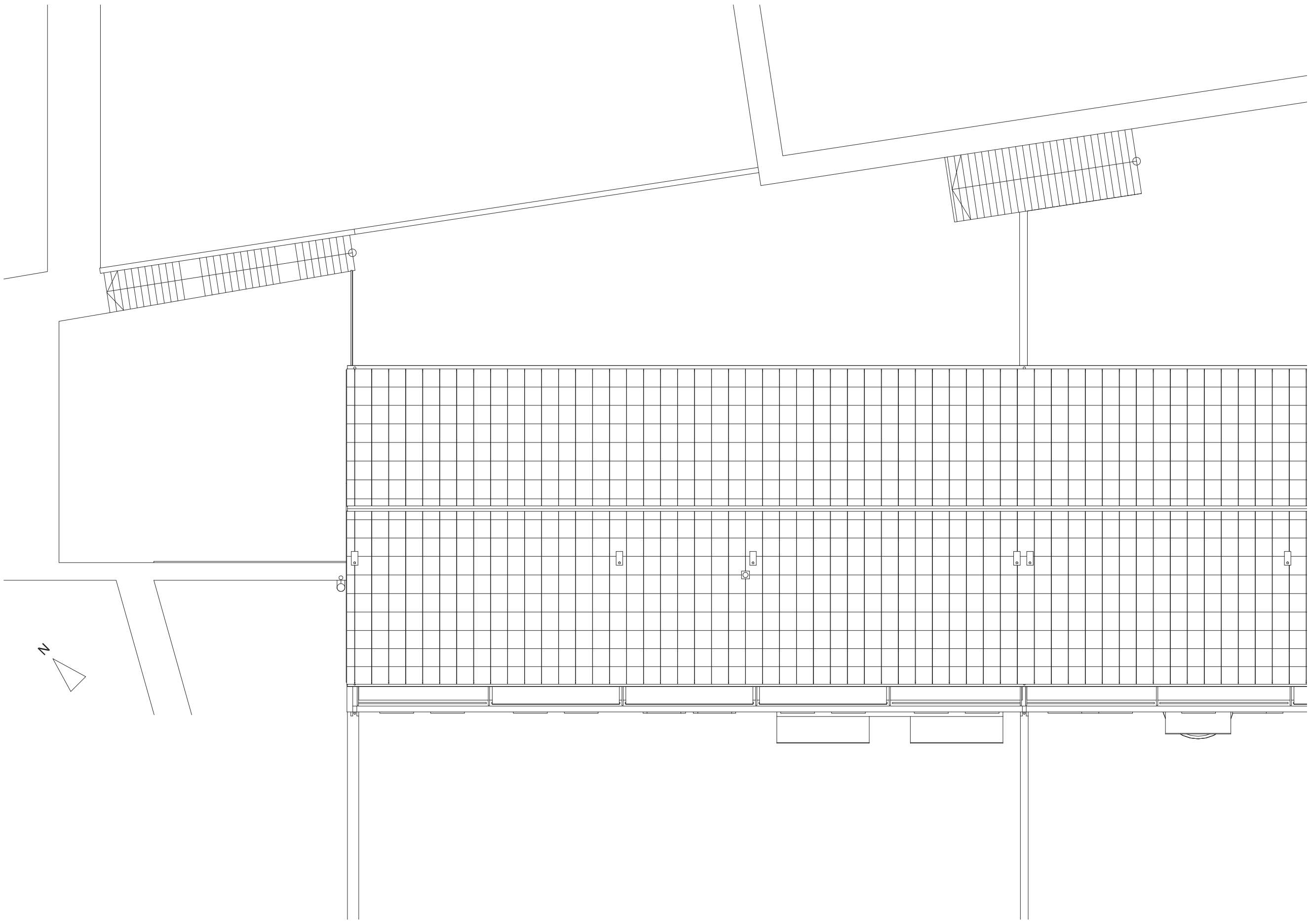
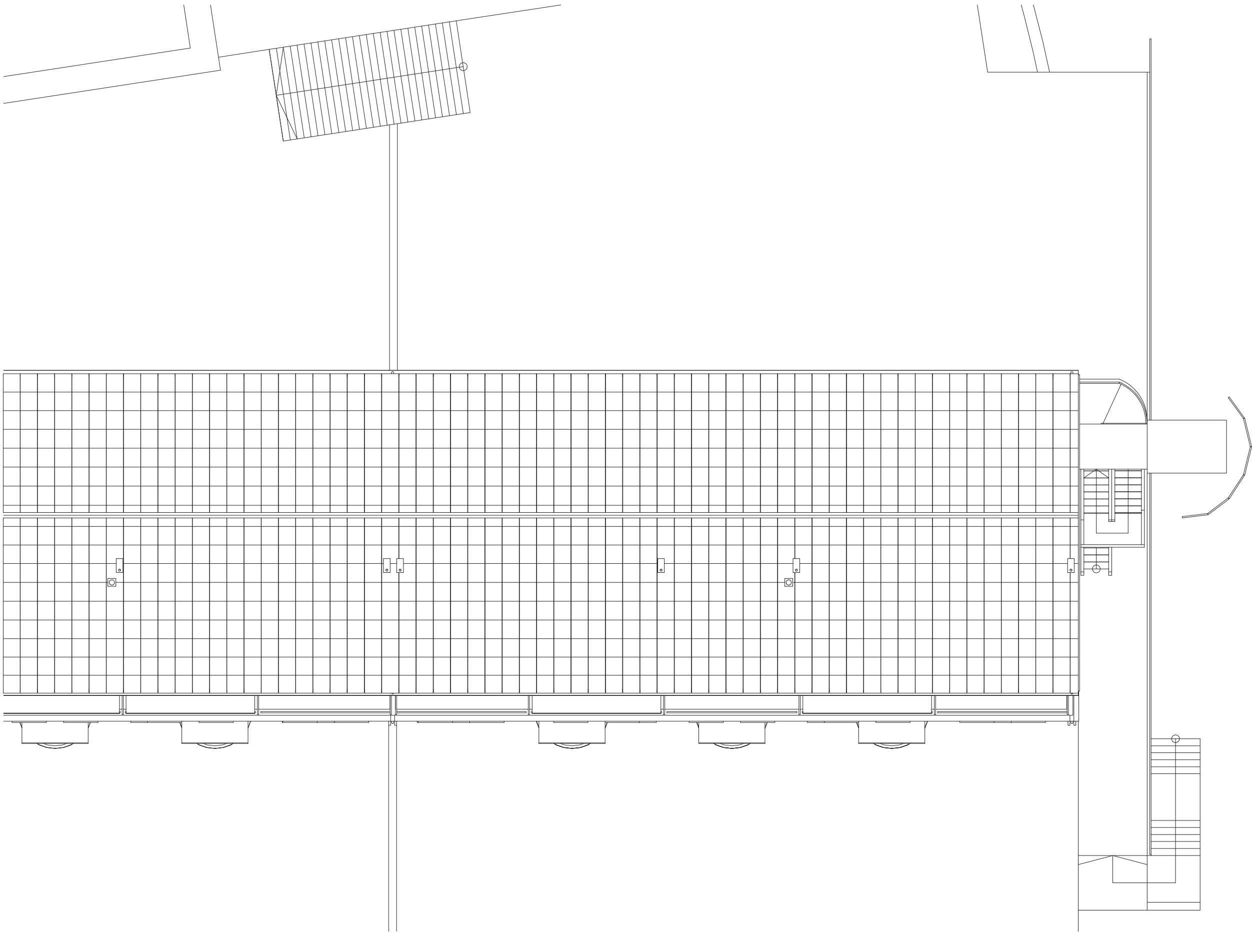


Figure 6-68. Design scenario S3-Transformation, Archetype 5.



5 4 3 2 1 0 m

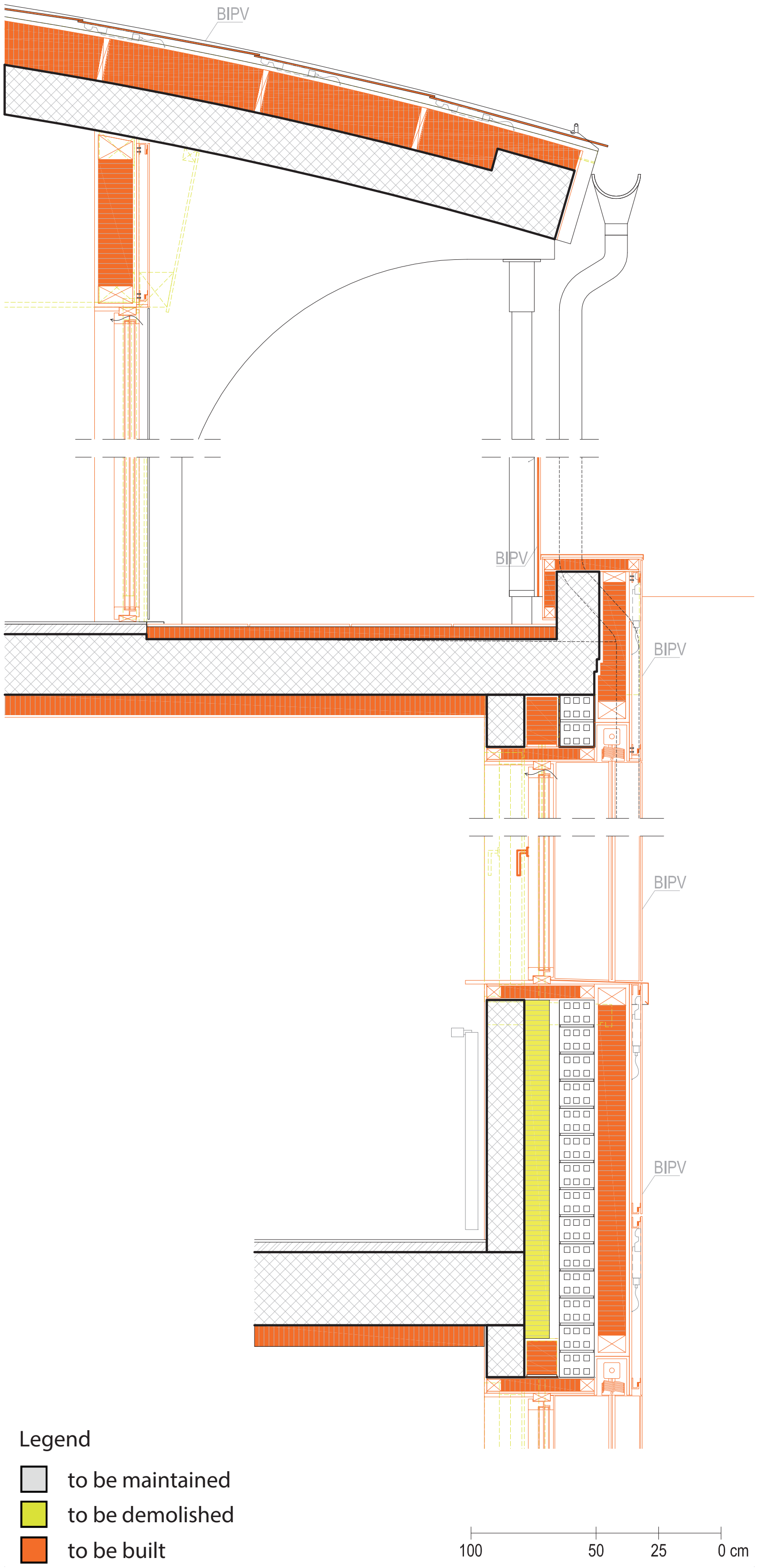


Figure 6-69. Façade constructive detail, **S3-Transformation**, Archetype 5.

Roof (curved): Standard-size PV panels with η-21.5% (STC), Air gap 5 cm, EPS expanded polystyrene 22 cm, Vapour barrier, Zinc sheet 0.5 cm, Air gap 5 cm, Vapour barrier, EPS expanded polystyrene (old) 8 cm, Reinforced concrete slab 20 cm.

Roof (flat): Concrete tiles 2 cm, XPS extruded polystyrene 4 cm, Bitumen 0..4 cm, Reinforced concrete slab 22 cm, EPS expanded polystyrene 10 cm, Vapour barrier, Plasterboard 1.5 cm.

Façade: Custom-size PV panels, light grey coloured film with η-11% (STC), Air gap 5 cm, Wood particle board 1.5 cm, EPS expanded polystyrene 15 cm, Wood particle board 1.5 cm, Ceramic brick 14 cm, Air gap 4 cm, EPS expanded polystyrene (old) 4 cm, Reinforced concrete 15 cm, EPS expanded polystyrene 13 cm, Plasterboard 1.5 cm.

Internal floor (against non-heated space): Timber floor 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm, EPS expanded polystyrene 10 cm, Plasterboard 1.5 cm.

External floor (ground): Ceramic floor tiles 1 cm, Cement screed 4 cm, Reinforced concrete slab 30 cm.

Solar protections: Exterior aluminium blinds 10 cm.

Balconies: Custom-size PV panels on railing, light grey coloured film with η-11% (STC), Reinforced concrete slab 30 cm.

Openings: Wooden frame windows with triple-glazing 4+12(argon)+6 mm+12(argon)+4 mm.

(Text in orange corresponds to added layers compared to the E0-Current status scenario.)

Potentially active surfaces

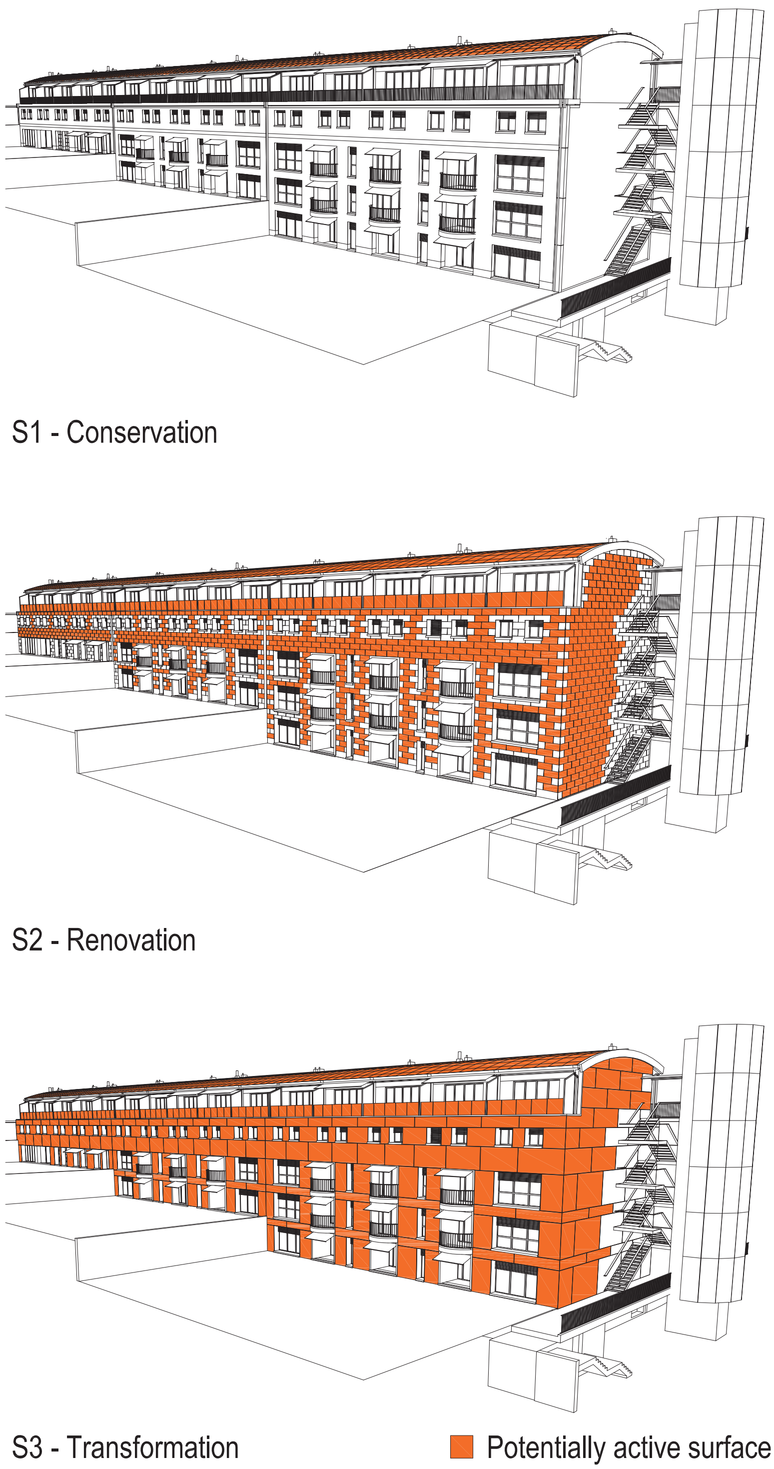


Figure 6-70. Potentially active surfaces detected for the different BIPV design scenarios, Archetype 5. Surfaces and equivalent power S1 (941 m^2 – 161 kWp), S2 (2’200 m^2 – 377 kWp), S3 (2’200 m^2 – 377 kWp).

Building envelope characteristics

S0 – Baseline	U-value
Roof curved– *ref. D01**	**U-0.25 W/m²·K**
Roof flat– *ref. Ds02**	**U-0.25 W/m²·K**
Façade – *ref. Ws11**	**U-0.59 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.01 W/m²·K**
Openings **	**U-1.30 W/m²·K**
Airtightness | Infiltration rate	*0.70 ACH*
S1 – BIPV Conservation	
Roof curved– *ref. D01**	**U-0.20 W/m²·K**
Roof flat– *ref. Ds02**	**U-0.25 W/m²·K**
Façade – *ref. Ws11**	**U-0.20 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.01 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.70 ACH*
S2 – BIPV Renovation	
Roof curved– *ref. D01**	**U-0.19 W/m²·K**
Roof flat– *ref. Ds02**	**U-0.25 W/m²·K**
Façade – *ref. Ws11**	**U-0.19 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.01 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.50 ACH*
S3 – BIPV Transformation	
Roof curved– *ref. D01**	**U-0.17 W/m²·K**
Roof flat– *ref. Ds02**	**U-0.25 W/m²·K**
Façade – *ref. Ws11**	**U-0.17 W/m²·K**
Internal floor (against non-heated space) – *ref. Bs03a**	**U-0.32 W/m²·K**
External floor (ground) **–** *ref. Bs14**	**U-2.01 W/m²·K**
Openings **	**U-0.77 W/m²·K**
Airtightness | Infiltration rate	*0.50 ACH*

Table 6-15. Final U-value of the different parts of the building envelope for each design scenario (E0, S0, S1, S2 and S3) for Archetype 5. Layers composition and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**. Detailed information in Annexe 10.1.7.

Thermal bridge analysis

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	+0.63	+0.61	+0.04	+0.04
TB2	-0.12	-0.08	+0.05	+0.07
TB3	+0.19	+0.17	+0.15	+0.15
TB4	+0.83	+0.78	+0.78	+0.71
TB6	+0.68	+0.66	+0.66	+0.62
TB7	-	-	-	+0.25
TB8	+0.06	+0.10	+0.14	+0.15
TB9	+0.09	+0.13	+0.11	+0.12
TB10	+0.11	+0.11	**+1.05**	**+0.16**
TB11	-	-	-	ΔU +0.03 W/m²·K

Values in **bold** have been calculated using the THERM software, all other values are adopted from the Swiss catalogue of thermal bridges [Infomind Sàrl 2003].

Table 6-16. Linear thermal bridges values for Archetype 5. Detailed information in Annexe 10.1.7.

Requirements comparison

Archetype 5	**Oil / Gas boiler**				**Heat-Pump**		
Requirements	S0	S1	S2	S3	S1	S2	S3
SIA 380/1:2016	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie® 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-P 2017 Renovation	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Minergie®-A 2017 Renovation	*NO*	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**
2’000-watt society	*NO*	*NO*	*NO*	**YES**	**YES**	**YES**	**YES**
Construction	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
Exploitation	*NO*	*NO*	*NO*	*YES*	*YES*	*YES*	*YES*
PV > 10 Wp/m² of ERA	*NO*	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

Table 6-17. Compliance check with energy requirements for Archetype 5.

6.5. Synthesis

The advantage of following a guideline marked by general design intentions is that it offers a series of intervention strategies which, although different for each building, allow a palette of comparable solutions to be provided. These solutions moreover allow meeting both the needs of the building itself and the demands of the surrounding environment.

Comparing the different implementations, in general it can be seen that the scenario S1-Conservation usually offers practically the same visual finish as the strategies commonly used by architects in the usual practice, introducing active surfaces in the less visible areas of the building such as the roof or using active elements that imitate – through shape, colour and texture – part of the building. The intention to integrate active elements with a conservationist objective does not modify the strategy adopted for the improvement of the thermal envelope.

In the case of the S2-Renovation scenario, the fact that there is a will to integrate active elements forces the designer to undertake an iterative design process that requires knowledge of the existing products on the market and the available personalisation techniques. In buildings where it is preferable to reproduce certain pre-existing elements such as the edges of windows or complex geometries such as in Archetype 4, the design must be simultaneously carried out at two scales (on a construction detail scale and on a global scale to verify the coherence of the design). In most of the implementations presented, this scenario shows the technical limit of this approach in light of the complexity of the proposed solutions. These constructive solutions designed to imitate what exists show that it is possible to give this type of response, but at the same time they show the need to reinterpret the building taking into account the particularities of the photovoltaic elements.

Without necessitating a deep knowledge in the matter of electricity and photovoltaic technology, the two main rules to respect are 1) to propose active elements of the largest possible size (to diminish the number of electrical connections) and 2) to design the minimum number of different elements at the level of quantity of photovoltaic cells, facilitating in this way the optimisation of the installation in terms of wiring, zoning and choice of inverters.

The implementation of the S3-Transformation scenario allows to obtain more coherent installations giving the possibility to improve the interior comfort conditions, such as through the increase of the glazed surfaces for a greater natural illumination or by offering larger exterior spaces (balconies). In certain cases, the use of darker contemporary colours, moving away from the original colours of the building, allows to increase the performance of the photovoltaic elements by avoiding the excessive reflection of light that occurs when using lighter colours.

The existing products on the mark*et all*ow to use all the opaque surfaces of the building envelope thanks to the fulfilment of the latest norms about products for buildings. Some companies propose mass-produced products with several possible sizes (Megaslate), offering a relative flexibility in the design of façades, but they are difficult to apply in renovation (conservation scenario). Especially because the proposed dimensions rarely match the dimensions that the existing building needs. However, at the time when more important interventions are proposed where the freedom of design is greater, these types of products have an important potential as they are produced in large quantities and therefore at reduced cost.

This type of products enables giving a transitory response that can highlight the possibility of using BIPV elements as building materials. From a design point of view, having to adapt an architectural design to a series of standard products represents an important barrier, mainly because architects need more freedom to be able to give a response adapted to each building. In the course of the thesis and as announced in Chapter 3, this limitation has already been overcome thanks to the synergies between the solar and glass industry. This union is promoting a paradigm shift and modifies the definition of *"standard panel"*, going from a panel produced in series with fixed measures to a panel manufactured according to the requirements of the architectural design (shape, appearance and layout of the pattern of photovoltaic cells) whose only limitation is the maximum size that is usually of 2.4x3.8 meters. This concept is already being applied in recent buildings such as the Silo Bleu in Renens (Switzerland) **[Epure Architecture 2019]** or in the Elithis tower in Strasbourg (France) **[XTU architectes 2017]**. The only requirement for such project initiatives is collaboration between the design team and the manufacturers of the photovoltaic modules from the initial stages of conception. This is the design concept applied in the proposals for the S3-Transformation scenario.

To further comment on the translation of the general strategies into concrete building-specific interventions, let us take Archetypes 1 and 2 as examples. These two buildings first appear as being similar, low-rise buildings with a large sloping roof. When considering the S1-Conservation scenario, this first snapshot of the buildings gives the impression that the same intervention strategy could be used for both buildings. This was precisely our initial reaction and we proposed an external insulation (ETICS) with a mortar finish as the original appearance.

Once the intervention completed, the resulting appearance is however very different for the two archetypes. While for Archetype 1 the objective of respecting the original appearance of the building is achieved without problems, for Archetype 2 this is not the case. Mainly, because the main peculiarities of this building are the proportions of the openings, its embrasures and shelves in stone imitation with a typical external wooden roller shutter, the geometry of the balconies and the imposing ground floor wall composed of limestone masonry that offer a very marked texture. These elements remain hidden or distorted if an external insulation is proposed, provoking an extrusion of the surfaces outwards and a decrease of window openings (by absorbing the embrasures and shelves in stone imitation that form the identity of the building). This is an example of how, in order to achieve the same general design objective, the strategy to be adopted is totally different. However, the energy efficiency objective in both cases is achieved with the same level of exigency, with an additional effort made for Archetype 2 in the control of thermal bridges and the risk of condensation.

The designs shown in this chapter correspond to the final designs that have resulted from an iterative process between the different phases of the thesis, especially between the design phase and the evaluation phase (Chapter 7). On a quantitative level, the simulation of the different proposals has allowed the adjustment / modification to achieve the desired efficiency objectives, as shown in Figure 6-71 (for minimum requirements) and Figure 6-72 (for Minergie® requirements).

Likewise, the qualitative evaluation conducted in the framework of the workshop with a group of experts (also in Chapter 7) has allowed refining the designs in two ways: 1) to be rigorous and credible from the point of view of professional practice, and 2) giving a more adjusted response to the different global design scenarios. As a result, a true palette of solutions has been obtained, ranging from an absolute respect for the existing status, to the reinterpretation of the renovation project based on the new reality offered by the photovoltaic industry, which allows us to achieve the 2050 objectives, and passing through intermediate solutions based on the mimicry of what exists, showing its limits and highlighting the need for a paradigm shift driven by environmental objectives.

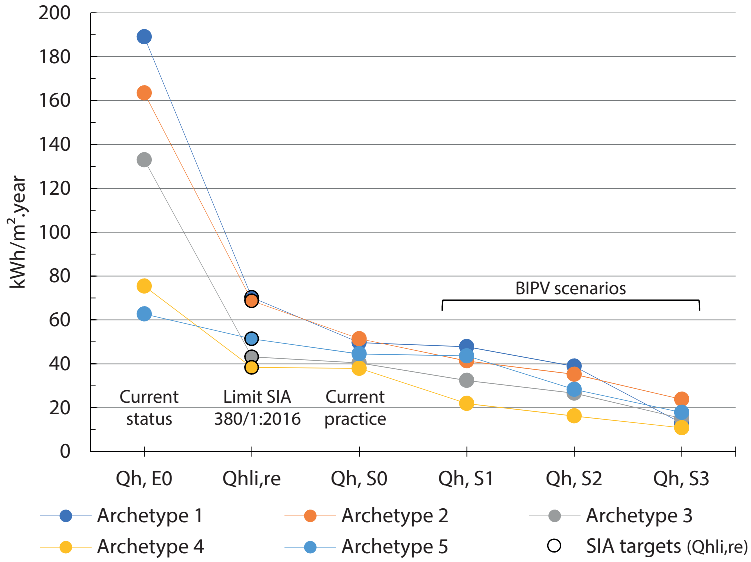


Figure 6-71. Heating energy needs limit (Qhli,re) and calculated (Qh) according to SIA 380/1:2016 **[SIA 2016a]** for the five archetypes.

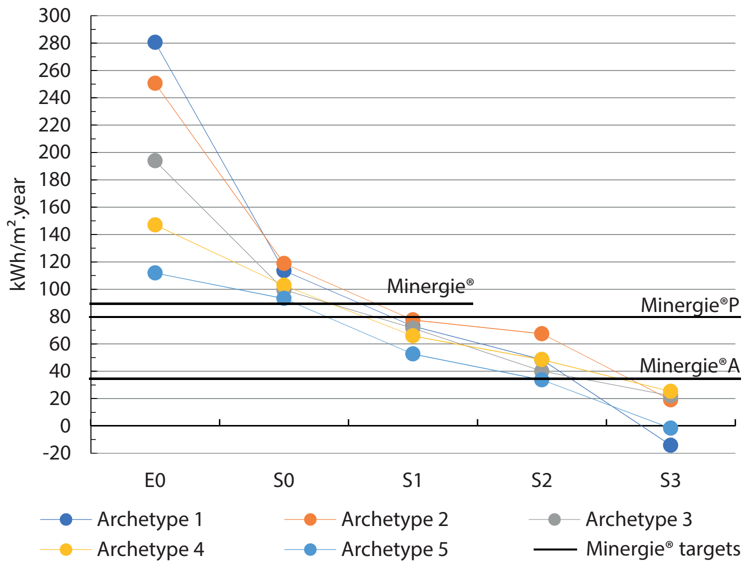


Figure 6-72. Energy balance calculated according to Minergie® standard for renovation projects for the five archetypes and including 100% of active surfaces (energy-use scenario A-100%).

7. Multi-criteria assessment

This chapter presents the method and results for evaluating each archetype and renovation scenario.

The complete evaluation is iterative and twofold (Figure 7-1). Described in Section 7.1, a qualitative assessment involving a group of experts was conducted during a workshop, where the intermediate results – in terms of architectural visualisations (computer-generated images), constructive details, and quantitative indicators – were shown for each scenario. This workshop allowed us to refine our final propositions in order to generate a series of convincing renovation examples using BIPV elements. The results of this workshop and the influence on the final propositions are exposed in Section 7.1.2.

Sections 7.2 to 7.4 are dedicated to the quantitative assessment of the scenarios, involving a series of indicators related to: 1) photovoltaic performance, 2) final energy balance, 3) life-cycle analysis (LCA), 4) life-cycle cost (LCC) and 5) indoor comfort. This assessment is fundamentally intertwined with the other phases of the methodology, in particular with Phase 3 (Chapter 6), as the indicators are calculated in an iterative way during the implementation of the renovation scenarios to verify the achievement of the objectives. Section 7.2 first describes the set of indicators evaluated, and the methods, workflows, and tools used to do so. Results of the assessment over the final propositions are presented per archetype in Section 7.3, and a discussion is presented in Section 7.4. The analysis includes: 1) the influence of the energy-use scenarios on the final performance of each BIPV renovation strategy in terms of energy, LCA and LCC, 2) the influence of the active surfaces selection procedure, 3) the importance of a self-consumption approach (no injection) versus a classical grid-injection approach (with a feed-in-tariff), 4) the role of batteries, and 5) the influence of the design-decisions on the final performance.

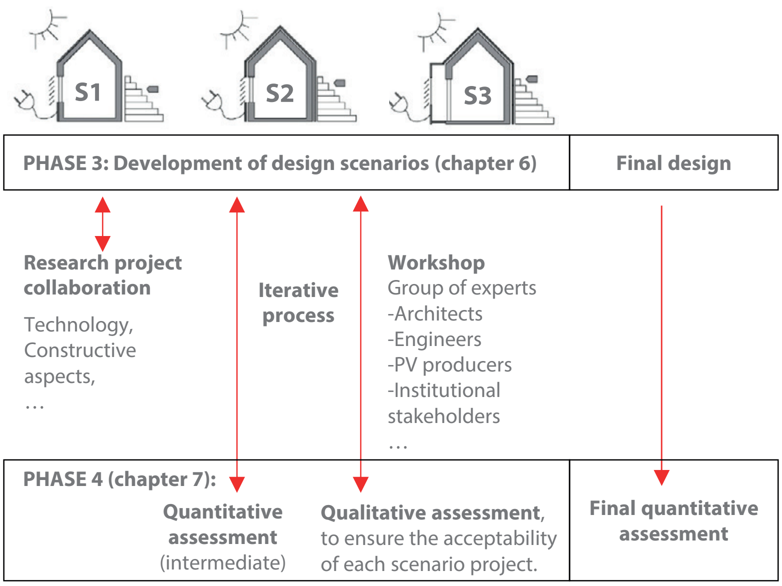


Figure 7-1. Overview of the assessment methodology and the iterative process between Phase 3 and 4.

7.1. Qualitative assessment

From an architectural practice point of view, if BIPV components are well implemented (as building material) in the design process, by taking into account the same criteria that we use in any architectural design, this kind of proposal will be accepted by the society more and more easily. The approach that we propose is based on an overview of the renewal process without focusing on acceptance as a purely visual aspect, in part because aesthetics is already an inherent issue in architectural projects, but also because this increased acceptance has the support of the regulations and strategies of many countries such as Switzerland.

To ensure that all proposals are evaluated not only in terms of quantitative criteria but also subjectively by a committee of experts, a protocol to judge the acceptability of the renovation projects was defined and applied in the context of a workshop. This section first describes the protocol, the involved methods, and the participants, before presenting the results from this qualitative assessment and how these influenced the refinement of the design scenarios.

7.1.1. Protocol for qualitative data collection

A one-day workshop was organised in June 2018 by the ACTIVE INTERFACES (AI) coordinators, with the aim of acquiring feedback from an interdisciplinary panel of actors (presented further below) on the relevance of the propositions developed in this thesis. This group of experts was solicited to critically assess and express their receptiveness towards the renovation scenarios.

The workshop was conducted in French and structured according to the program of Table 7-1. As introduction, information about the AI project was given by the principal investigator (PI), and the research context and objectives were presented. The core of the workshop consisted in using two techniques to gather feedback from the participants. First, discussions or focus groups were held during the morning, and results were then presented in a plenary session. In the afternoon, two live surveys were conducted in a plenary session. More details on these two approaches are given below. The day then concluded with a synthesis presented by the PI of the AI project.

9:30	Welcome of participants	
10:00	General introduction	*Information on project and workshop program, presented by PI*
10:30	Group discussions	*Five focus groups, one case study per group, one moderator per group*
11:30	Synthesis of discussions	*Plenary, moderated by subproject PI*
12:30	Lunch	
13:30	Live survey: Evaluation of the architectural integration	*Session with clickers*
14:45	Break	
15:05	Live survey: Impact potential of project	*Session with clickers*
15:45	Synthesis and final discussion	*By project PI*
16:00	End of workshop	

Table 7-1. Program of workshop day.

Participants and involved researchers

Five members of the AI research project, including its PI, participated in the workshop. Each member took over the role of moderator during the focus groups session, as further explained below.

Professionals within the contact networks of members of the AI project and belonging to a category of BIPV actors – architects, engineers, manufacturers, public services representatives (institutional), and contracting authorities (owner) – were invited to participate to the workshop by email. Although the initial objective was to recruit an equal number of representatives from the five categories listed above, this proved to be difficult. In total, 21 professionals participated to the morning session and one more joined for the afternoon. The distribution of profiles based on the current function of the participants is shown in Figure 7-2. As can be seen, architects were the most represented group (41%), followed by PV industry representatives (27%). Two persons for each of the categories (9% each) of building engineers, PV experts, and public sector representatives (institutional), and one façade expert (5%) completed the whole. No building owner was present.

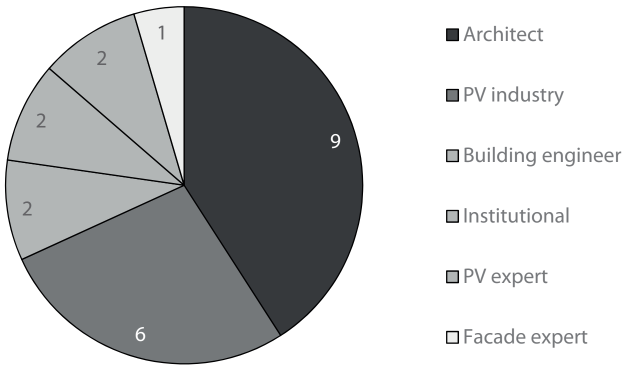


Figure 7-2. Number of participants according to their current function (total of 22 participants). One of the architects took part only in the afternoon sessions.

Focus groups

Focus groups are a common research tool for qualitative data collection [**Morgan 1996; Langford et al. 2002**]. It allows capturing the perceptions of the group members on the topic of interest, through a planned discussion facilitated by a moderator [**Langford et al. 2002**]. This technique is used in many fields including social sciences, marketing research, and product and system design to gather knowledge from intended users [**Langford et al. 2002**].

One of the key advantages of a focus group, in comparison to individual interviews, lies in the interactions between group members. It is argued that the discussion process leads to a collective view that is greater than the sum of the individual parts [**Morgan 1996; Maguire 2001**]. By confronting points of views, information can be gathered on the level of consensus versus divergence among participants. However, this advantage can simultaneously be a disadvantage as the responses from the participants are no longer independent and can be influenced by the most outspoken person [**Stewart et al. 2015**].

To ensure the group is manageable by the moderator, its size should not exceed 12 participants [**Langford et al. 2002; Stewart et al. 2015**]. In terms of minimum size, recommendations differ from five [**Langford et al. 2002**] to eight, which [**Stewart et al. 2015**] consider more appropriate to limit the risk of having one or two members dominate the discussion. In our case, each group was composed of four to five participants. This number was not fixed in advanced, but rather a consequence of the total number of participants who were divided into a fixed number of five groups (one group per archetype).

The amount of focus groups to conduct depends on the context of the study, in particular on the diversity of the participants, the range of topics addressed, and whether a segmentation strategy is used **[Morgan 1996]**. The latter refers to cases where feedback is sought from different homogeneous groups. For example, in our context, this would mean having disciplinary groups (i.e. one group of architects, one of engineers, etc.). However, our strategy was opposite as interdisciplinary groups were formed. The number of groups was here dictated by the amount of case studies (five). This number falls within the range of number of groups commonly encountered, which is between four to six **[Morgan 1996]**.

A guide including questions developed prior to conducting the focus groups is commonly used by the moderator **[Stewart et al. 2015]**. In our case, a file was prepared for each case study including detailed information on the renovation interventions and BIPV strategies, as well as multiple drawings (e.g. of construction details) and computer-generated images of the different proposals (similar to the elements presented in Chapter 6). In addition, a poster on the corresponding case study was positioned near each focus group table (see Figure 7-3). It included results from the quantitative assessment of the scenarios including all performance indicators (final-energy balance, photovoltaic performance, indoor comfort, LCA and LCC). To capture participants' spontaneous reactions, no specific questions were prepared; the discussion occurred naturally from the basis of examining the available material, keeping in mind the goal of collecting participants' opinion on the proposal.

While there is no unique way of analysing and reporting the outcomes from focus groups, common methods include transcribing the discussions and extracting the main conclusions **[Stewart et al. 2015]**. The task can be difficult given the open-ended format of the discussion **[Stewart et al. 2015]**. In our case, one participant per group was designated to summarise the discussion during the plenary session dedicated to the synthesis of the focus groups (see Figure 7-3). Main group results are summarised in Section 7.1.2.

Live survey

It is typical to combine a focus group study with another data collection method **[Morgan 1996; Saunders et al. 2013; Meex et al. 2018]**. This complimentary method often involves a higher number of respondents. However, in our case, the objective was not to gather quantitative data (e.g. for statistical analysis) or to generalise the observations from the workshop. Rather, the goal was to complement the focus group discussions, where participants were exposed to only one archetype, with a plenary session where every design alternative was presented to all participants. As such, a live survey was chosen as a means to collect answers to close-ended questions, thus complementing the open-ended discussions from the focus groups.

An audience response system proposed by the teaching support centre at EPFL **[EPFL 2018]**, a 'clicker box', was distributed to each participant. This device allows casting a vote, in an anonymous way that is then recorded in real-time. Once all participants have cast their vote, aggregated answers can be displayed in a bar graph on the screen (through MS Powerpoint).

Two such clicker sessions were held. A first one consisted in iteratively asking the same question for each scenario of each case study, to inquire about the desirability of the architectural integration of the proposal. This led to a total of 15 instances of the question (once for each of the three BIPV scenarios S1-S3 of each of the five case studies).

A second clicker session was later conducted to assess the impact potential of the ACTIVE INTERFACES project as a whole. A series of 11 general questions on the impact potential of all the work realised in the framework of the project were asked, again with a pre-defined list of answers to choose from in real-time.

The questions and answers for both clicker sessions are shown in the next section.

Figure 7-3. Photos from the workshop day: presentation of the case study by the moderator (S. Aguacil) of one of the focus groups (top), and restitution of the discussion by a participant to one of the focus groups (bottom).

Online survey

In light of the outcomes from the workshop day, modifications were made to some of the scenarios, leading to the final propositions shown in Chapter 6. An online survey was then sent (4 months after the workshop) to the same group of participants, to collect their opinion on the final scenarios. The survey consisted in the same question as in the first clicker session, about the desirability of the scenarios. This time, only the computer-generated image was shown for each scenario of each archetype, along with the main interventions (short text). No information on the performance evaluation and no drawings of the constructive details were included. Seventeen of the 22 workshop participants answered the survey.

7.1.2. Results

We here present the outcomes of the qualitative assessment by relating the reactions from the panel of experts first to each scenario of each archetype, second concerning the overall impact potential of the project, and third on different aspects related to the research topic.

Assessment of proposed designs

The assessment of the different scenarios includes some elements from the focus groups, and the answers to the live clicker survey held during the workshop (W) and to the online questionnaire (O) on the desirability of the proposals.

Table 7-2 presents a summary of the comments made by the participants during the focus groups on the visual appearance and construction aspects. The corresponding responses and entailed actions, i.e. the refinements of the design propositions, are commented alongside. For four propositions, changes were brought to the external building envelope, visible in the final renderings.

One particular opinion was shared among a majority of the participants: that, given the intention set for the S3 scenarios, i.e. allow a complete transformation of the building expression, some designs were not 'extreme' enough. Therefore, three S3 scenarios were adjusted following the workshop.

The visually modified scenarios are shown in their version presented during the workshop versus in the online survey in Figure 7-4 to Figure 7-7, along with details on the modifications made.

Table 7-2. Summary of assessment of proposals by participants during focus groups. No specific comments were made for Archetype 3 (for which all scenarios were globally accepted as seen in Figure 7-8).

Arch.	Comments on visual appearance and construction aspects	Response and entailed action
1	Very little variations between the scenarios, in particular between S1 and S2 (subtle differences, difficult to see).	No changes were made to S1 and S2 (differences were explained more clearly during the workshop).
	S3 could be more "aggressive".	Modifications were made to S3 (see Figure 7-4).
2	Why balconies are kept as is in S2-S3 and not cut off or enlarged?	Balconies have been enlarged and substituted in S3 (see Figure 7-6). They have been conserved for S2 due to their role in defining the expression of the building.
	Important to address thermal bridges.	Not shown during the workshop but already done.
	Aesthetic loss in S3 with the covering of the foundation by PV elements, also given the low PV yield at that lower level and safety concerns with having glass panels near a garden area at reachable height.	Given the intention for S3, this transformation of the foundation level is considered permitted, but is not necessarily active (depending on sizing scenario). Safety issues are considered limited since the garden is private (internal courtyard) and as multiple examples can be found of glass components at reachable height.
	Could go further with S3 and completely redefine the building.	The newly proposed S3 does include more drastic interventions (e.g. balconies).
3	-	-
4	Important to address thermal bridges.	Not shown during the workshop but already done.
	S2 is less satisfying since it appears complicated to implement; the appearance is conserved but not the general proportions of the building (external insulation added).	The proposition is maintained to show the limits of a mimicry approach.
	For S3, since the appearance is allowed to change more drastically (and the proposal does so to some extent), why not take more freedom in going even further with the intervention and be more creative.	S3 has been changed mainly to propose larger openings (see Figure 7-7).
5	For S2, the proposed non-active façade using Eternit, hiding the brick wall (of high-quality) is criticised, especially since there is no need to add a lot of insulation for this relatively recent building.	Following the mimicry approach, the brick façade in S2 has been reinterpreted but with active elements.
	Important to address thermal bridges.	Not shown during the workshop but already done.

Figure 7-4. Archetype 1, S3-Transformation, in its initial status (workshop; left) and final status (online survey; right). Changes: instead of reproducing original colours and textures, the final solution consists in going for more contemporary colours and active elements with homogeneous / matt aspect instead of mortar textured modules trying to imitate the original aspect. Balconies are substituted with larger ones and the balcony of the 4th floor is unified.

Figure 7-5. Archetype 2, S1-Conservation, in its initial status (workshop; left) and final status (online survey; right). Changes: instead of proposing an external insulation trying to reproduce the main peculiarities of this building (proportions of the openings, embrasures and shelves in stone imitation with a typical external wooden roller shutter), the final solution consists in an internal insulation to avoid the problem of hiding or distorting these elements that give the character to the building.

Figure 7-6. Archetype 2, S3-Transformation, in its initial status (workshop; left) and final status (online survey; right). Changes: the biggest changes proposed for the final version are the replacement of balconies (by larger, prefabricated ones) and the change in the size of the BIPV elements and their pattern distribution to emphasise the horizontal expression of building façade. The traditional roller blinds are replaced by venetian blinds.

Figure 7-7. Archetype 4, S3-Transformation, in its initial status (workshop; left) and final status (online survey; right). Changes: for the final version of the project, openings are enlarged, reinterpreting the formal aspect of the building and allowing more daylight to enter the apartments, avoiding the issues highlighted for the previous design that was judged as not sufficiently *"aggressive"* given the name of the design scenario *"Transformation"*.

Responses to the desirability question are shown in Figure 7-8. An asterisk identifies scenarios that have changed visually between the day of the workshop and the time of the online survey.

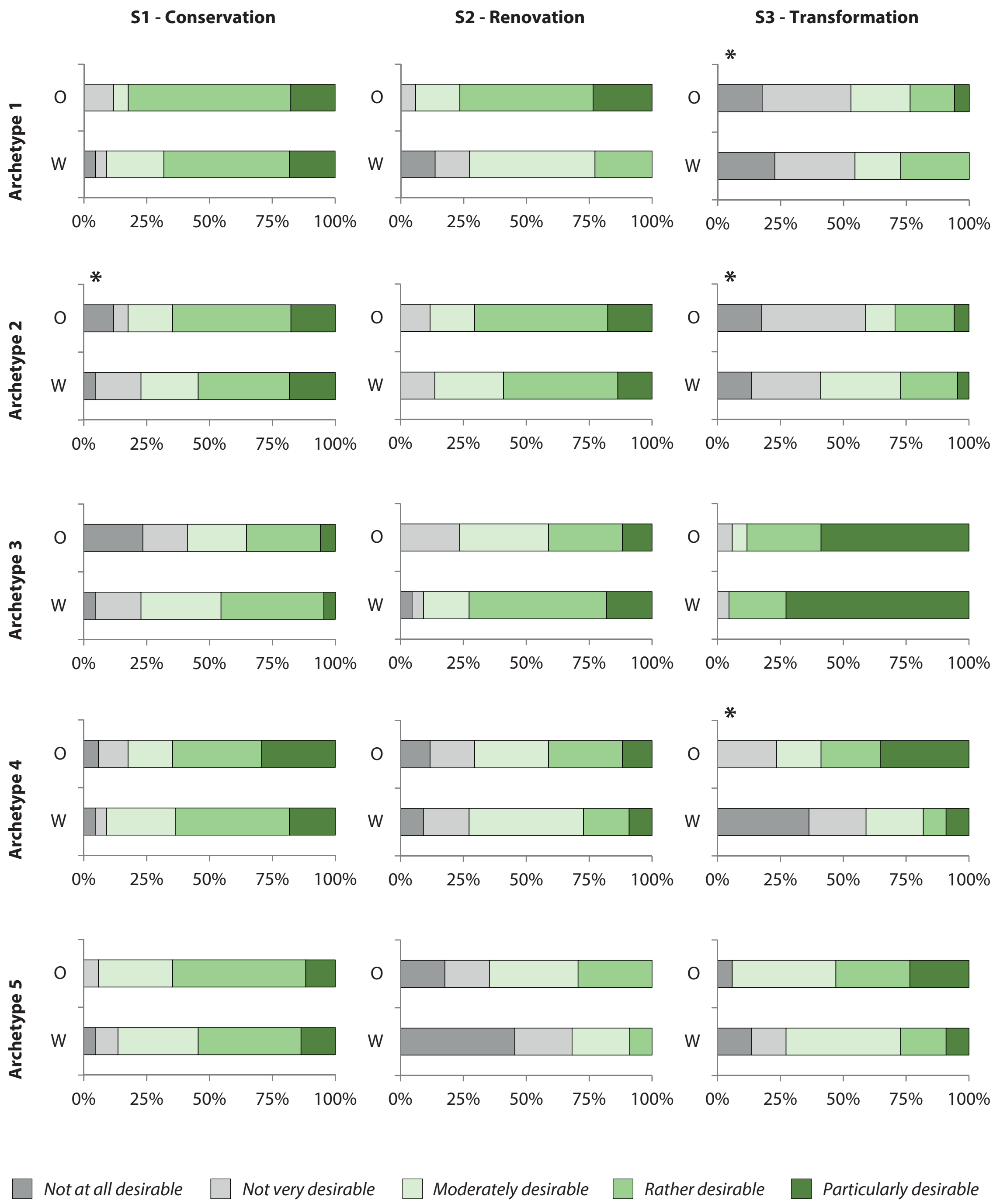
From Figure 7-8, it can be observed that the least accepted scenarios are: S3 from Archetype 1, whose post-workshop modifications caused a slight shift towards a positive rating; S1 and S3 from Archetype 2, both modified after the workshop, leading respectively to an improvement and slight setback; S3 from Archetype 4 which shows much higher desirability following its modification; and finally S2 of Archetype 5, which, despite not having been changed, shows a higher desirability from the online survey than at the time of the workshop. It must be noted that, since participants were exposed to much more information regarding the different scenarios during the workshop, their answers during the clicker session might have been influenced by other aspects than purely that of the architectural integration.

Another observation to be made is the divergence among the opinions of the practitioners for a given scenario. Indeed, in almost all cases, there is at least one selection of each of the five possible answers, meaning that ratings range from not at all to particularly desirable for a same scenario. These results demonstrate the high subjectivity of the architectural integration qualities of a renovation project.

Since the objective of this assessment is not to identify any one 'best' solution, but rather to verify if all solutions are 'acceptable', we conclude that all scenarios are valid, with some being more convincing than others.

Figure 7-8. Distribution of participants' answers to the question (see top) asked on the evaluation of the architectural integration for each scenario of each archetype, during the workshop clicker session (W; 22 respondents) on the scenarios in their status at the time of the workshop, and through an online survey sent some months after the workshop (O; 17 respondents), showing the computer-generated images of the scenarios in their final status (shown in Chapter 6). Scenarios that have changed visually are identified by an asterisk (*).

According to you, in terms of architectural integration, is the proposed scenario…



Assessment of the impact potential of the research

Figure 7-9 shows the participants answers to the 11 questions asked during the second clicker session. The questions relate to the overall AI project and aimed at assessing the impact potential of the research and getting insights into the perception of the participants on the status of BIPV in practice.

The points on which a large majority of practitioners agreed include two of the barriers highlighted in Chapter 3: the need for more documented pilot project with BIPV (question 3; 95% *"yes"*), and the low level of knowledge on BIPV (question 4) among both architects (23% *"null"*, 73% *"weak"*) and contracting authorities (59% *"null"*, 36% *"weak"*).

A large majority also agreed on the rise in importance of BIPV (question 9; 91% *"yes"*), and the positive perception of the evolution of BIPV (question 10, 86% *"extremely"* or *"somewhat"*). A less important majority answered positively to questions 1 on the need to develop more BIPV products (73%) and 2 on the relevance of integrating BIPV in prefabricated elements as a strategy for BIPV diffusion (77%).

For the other questions, responses are more distributed across two or more different possible answers. In question 6, respondents were almost equally split between contracting and public authorities as being the most important actor for the diffusion of BIPV. A comment was made on the absence of architects and building engineers as a possible answer.

A small majority answered *"no"* to question 7 on whether the subsidy policy supports BIPV diffusion, possibly since the current subsidy strategy is based uniquely on a quantitative criterion (nominal installation power), and gives no consideration to qualitative aspects.

There was an almost equal split on whether difficulties of obtaining a construction permit is an obstacle for BIPV diffusion (question 8) between *"no"* (41%) and *"yes, but a necessary obstacle to guarantee project quality"* (45%), with a smaller percentage thinking that permits should be granted more easily (14%). A majority is thus not in favour of relaxing constraints in the construction permit procurement process.

Finally, in question 11 – regarding the expected level of influence of the project's proposals on the professional practice of the participants – there were mixed answers although a majority (77%) selected *"somewhat"* or *"maybe"*.

It is important to highlight that these results are influenced by the fact that each stakeholder group was not equally represented in the participants (dominance of architects, see Figure 7-2).

To complement these answers, we now look back to the focus group discussions from which additional points emerged regarding various topics related to the research project.

Figure 7-9. Distribution of answers to the different questions for assessing the impact potential of the overall project (second clicker session; 22 participants). Translation from the original questions (in French).

1. Must we continue to develop more BIPV products in terms of colors and textures to answer to the lack of esthetics often associated to photovoltaic?

No, the market already proposes enough adapted BIPV products from an esthetical point of view.	27%
Yes, the BIPV solutions currently available on the market are not sufficient.	73%

2. In your opinion, does the integration of BIPV in prefabricated construction elements (railing, windows, facade elements including insulation, etc.) represent a strategy allowing to accelerate the diffusion of BIPV?

Yes, the idea of directly proposing a finished product that includes BIPV can facilitate its adoption.	77%
No, such prefabricated elements cannot be standardized with BIPV.	23%

3. Would more pilot projects with BIPV, detailed and documented (products used, costs, financing, commissioned actors, etc.), be useful for you?

No, the documentation of pilot projects is not useful to me.	5%
No, there are already enough documented pilot projects.	0%
Yes, further documented cases would be useful to me.	95%

4. How do you evaluate the knowledge of BIPV in general among…

…architects?

Good	0%
Sufficient	5%
Weak	73%
Null	23%

…contracting authorities?

Good	0%
Sufficient	5%
Weak	36%
Null	59%

6. In your opinion, who is the most important actor / stakeholder for the diffusion of BIPV in Switzerland?

Contracting authorities	50%
BIPV manufacturers and providers	5%
Energy distributors (Groupe E, Romande Energie, BKW, Viteos, etc)	0%
Public authorities (confederation, cantons, communes)	45%

7. Do you think that the current subsidy policy for photovoltaic installation supports the diffusion of BIPV?

I don't know	14%
No	64%
Yes	23%

8. According to you, is the difficulty of obtaining a construction permit for a BIPV facade a major obstacle for the diffusion of BIPV?

No, it does not represent a real obstacle.	41%
Yes, but it is an obstacle that it is necessary to maintain to guarantee quality projects.	45%
Yes, construction permits for BIPV projects should be granted more easily.	14%

9. According to you, will the importance of the BIPV issue rise in the years to come?

No	9%
Yes, in a distant future	36%
Yes, in a near future	55%

10. Overall, do you perceive the evolution in the BIPV domain in a positive manner?

A lot	50%
Somewhat	36%
Maybe	9%
Not really	5%
Not at all	0%

11. Will the solutions presented during this workshop influence your professional practice?

A lot	0%
Somewhat	41%
Maybe	36%
Not really	18%
Not at all	5%

General feedback on research topic

The main points raised by one or more of the focus groups are here summarised and discussed.

Some questions were raised regarding aspects that are not directly addressed in this work (out of the scope), such as safety and fire concerns (dedicated standards are in force and evolving [**EU 2011; Erban 2016**]), the combination of solar thermal with PV, and the repartition of economic savings between owner and tenant. This latter point seemed to be an important concern for many practitioners, together with other elements related to building owners, e.g. whether they have an obligation to renovate, and what are the incentives for them to do so (since the architectural considerations put forward in this work are not determining factors for them).

In terms of legal obligation, the owner has to maintain the building; when the moment comes that there is a need to e.g. repair the façade, the law obliges to comply with the MoPEC **[EnDK 2014]** following the requirements published in SIA 380/1:2016 (for renovation).

The belief that the proposed strategies are difficult to justify economically, which seemed shared among a majority of participants, is in line with the corresponding barriers highlighted in Chapter 3. It also relates to the 5% interest rate commonly aimed for, which is no longer reasonable as discussed in Section 3.1.2.

In light of these raised points, the economic calculations (presented in the next section) were deepened with the possibility of comparing the financial consequences of different scenarios in terms of BIPV sizing, energy-use, subsidies, etc. Moreover, while only the payback time was shown during the workshop, other indicators were added (e.g. internal rate of return, net present value).

Questions related to how to attribute the savings and whether to increase rent could be supported through new business models such as contracting offered by an Energy Services Company (ESCO) as discussed in Section 3.2.3.

In this thesis, the architect is given a key role in having to defend and convince owners of the relevance of the renovation strategies. This is why different levels of interventions are proposed and documented, making it possible to see what is 'lost' by a shallow renovation (opportunity cost) or how a deep intervention with BIPV can be cost-effective.

Since it was not possible to communicate all information to the participants on the method, assumptions, verifications, etc., some questions raised concerned aspects that are indeed addressed in the research, but that were not explicitly shown or discussed during the workshop. The fact that these elements were brought up reinforces the necessity of incorporating them in the evaluation. Examples are the inclusion of certain costs (e.g. maintenance fees, which are indeed taken into account), and concerns around injecting too much electricity into the grid and the need for storage. The latter was due to the fact that out of the three BIPV sizing options considered – A-100%, B-Selection, C-Batteries (introduced in Chapter 6) – only the first one was shown, which, as seen in the next section, has an extensive amount of BIPV that can lead in some cases to a low self-consumption.

These highly active envelopes also triggered some questions on the implications in terms of embodied energy, in comparison with the relatively 'clean' Swiss grid. In reaction, the calculation of the levelized cost of energy (LCOE) and the environmental impact (Non-renewable primary energy and carbon content) per kWh of electricity produced by the BIPV installation is conducted in order to compare with the Swiss grid.

Suggestions were made, such as to consider having communities of self-consumption in cases of high production but low self-consumption at the building level. Although this is judged (by participants themselves) as currently complex to implement for owners, the Swiss Energy Law in force since January 2018 in fact aims at making it easier to share PV electricity through the development of such microgrids. In the context of this thesis, focus was placed on the building scale, but this option could be investigated in future work.

It was also suggested to consider other environmental indicators such as eco-points (UBP) [**Frischknecht et al. 2013; KBOB 2016**]. This could also be included in further work, to complement the set of calculated indicators that were chosen in part because they are internationally used and recognised.

Overall, the workshop and online survey allowed getting external views on the project before its end. These insights from a professional perspective were useful in bringing refinements not only to the designs, but also to the quantitative assessment presented in the following section.

7.2. Quantitative assessment

This section describes the methodology and workflow for conducting the quantitative assessment.

First, the assessment indicators are defined in Section 7.2.1. The evaluation workflows and the methods and tools used, including a custom prototype tool developed in the MS Excel environment, are presented in Section 7.2.2.

Sections 7.2.3 and 7.2.4 are respectively dedicated to the description of the energy-use variants (in terms of BIPV sizing, storage, and grid-export) and the active surfaces selection method [**Aguacil et al. 2019**], developed to define the energy-use option B-Selection.

7.2.1. Indicators

The whole set of indicators assessed in this quantitative multi-criteria evaluation of the design scenarios are listed in Table 7-3, according to their classification into the following five groups:

Photovoltaic performance

Although an objective of the thesis is to provoke a change of paradigm in the way a photovoltaic installation is assessed, moving away from considering it in separation from the renovation project, it remains interesting to verify the efficiency of the installation itself. Isolating the effect of the BIPV installation, a set of indicators are computed in order to obtain an overview of the general performance of the installation planned for each scenario, based on the energy and economic cost of the implementation.

Final energy balance | Operational phase

Indicators evaluating the final building performance during the operational phase (energy consumption due to the daily use of the building, in terms of heating, appliances, lighting, ventilation and domestic hot water), including the contribution of the PV-electricity.

Life-Cycle Analysis (LCA) | Operational and construction phase

To evaluate the whole renovation project including energy consumption, embodied energy of the construction materials and BIPV elements, an LCA is conducted, with results expressed in terms of energy and GHG emissions.

Life-Cycle Cost (LCC)

In order to evaluate the cost-effectiveness of the different renovation scenarios, various economic indicators are computed over mid/long-term investment horizons.

Indoor comfort

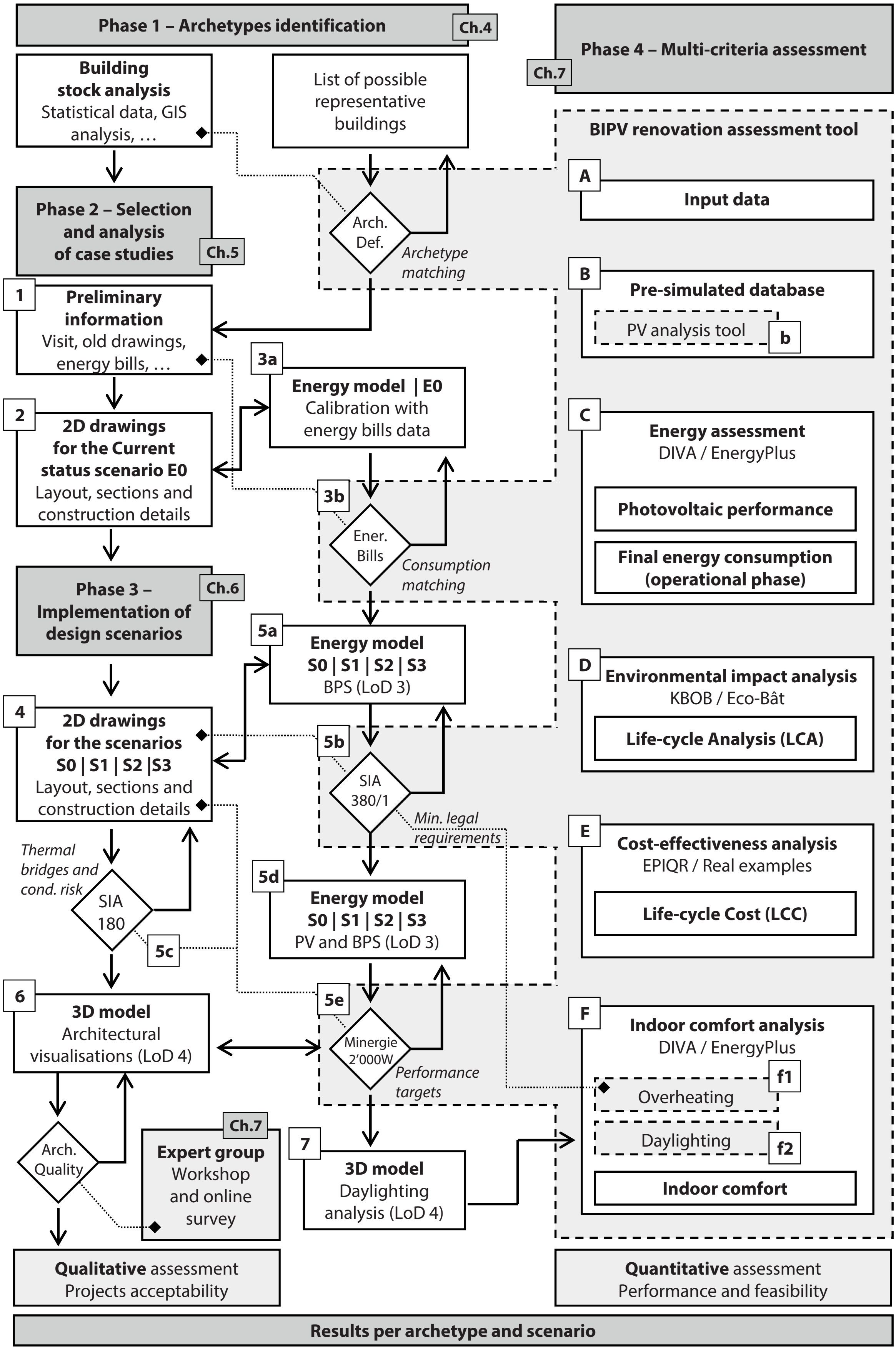
To verify the impact of the renovation strategies on the indoor comfort of the occupants, indicators related to the daylighting potential and the risk of overheating are evaluated.

Indicator	Units	Method - tool	LoD
Photovoltaic performance			
Levelized Cost of Energy ($LCOE_{PV}$)	$CHF/kWh_{e\text{-}pv}$	1, 2	LoD3
NR Primary Energy Factor ($NRPEF_{PV}$)	$kWh_{NRE}/kWh_{e\text{-}pv}$	1, 2, 3, 4, 5	LoD3
Carbon Content Factor (CCF_{PV})	$kgCO_{2\text{-}eq}/kWh_{e\text{-}pv}$	1, 2, 3, 4, 5	LoD3
Energy Payback Time ($EPBT_{PV}$)	years	5, 6	LoD3
GHG Emissions Payback Time ($GPBT_{PV}$)	years	5, 6	LoD3
Energy yield	$kWh_{e\text{-}pv}/kWh_p$	1, 2, 3, 4, 6	LoD3
Final energy balance | Operational phase			
Power needed for heating and DHW	kW	1, 2, 3, 4, 5	LoD3
Final energy consumption (FE)	$kWh/m^2{\cdot}year$	1, 2, 3, 4, 5, 11	LoD3
PV electricity self-consumed by bldg (PVSC)	$kWh_{e\text{-}pv}/m^2{\cdot}year$	6	-
PV electricity injected into grid (PVI)	$kWh_{e\text{-}pv}/m^2{\cdot}year$	6	-
Self-consumption rate (SC)	%	6	-
Self-sufficiency rate (SS)	%	6	-
NR Cumulative Energy Demand (CEDnr-op)	$kWh_{NRE}/m^2{\cdot}year$	5, 6	-
Global Warming Potential (GWP-op)	$kgCO_{2\text{-}eq}/m^2{\cdot}year$	5, 6	-
Life-Cycle Analysis (LCA) | Operational and construction phase			
NR Cumulative Energy Demand (CEDnr)	$MJ_{NRE}/m^2{\cdot}year$	5, 6, 11	-
Global Warming Potential (GWP)	$kgCO_{2\text{-}eq}/m^2{\cdot}year$	5, 6, 11	-
Energy Payback Time (EPBT)	years	5, 6	-
GHG Emissions Payback Time (GPBT)	years	5, 6	-
Life-Cycle Cost (LCC)			
Investment cost (I)	CHF/m^2 or CHF	6, 7, 8, 9, 10, 12	-
Net present value (NPV)*	CHF/m^2 or CHF	6, 7	-
Internal rate of return (IRR)*	%	6, 7	-
Discounted payback time (DPBT)	years	6, 7	-
Simple payback time (SPBT)	years	7	-
Indoor comfort			
Daylit Area ($sDA_{100lux,\ 50\%}$)	% of floor area	2, 3, 4	LoD4
Overheating hours (hrs when T>26.5°C)	hours/year	1, 11	LoD3

References: 1. EnergyPlus, 2. DIVA, 3. Radiance, 4. Daysim, 5. KBOB, 6. MS Excel, 7. DCF, 8. EPIQR, 9. Example projects, 10. BIPV reference prices, 11. SIA norms (e.g. 380/1:2016, 2024:2015), 12. OFEN PV prices market study. *Investment horizon adopted: 30 years with 3% of interest rate.

Table 7-3. Overview of the assessment indicators, calculation data / tool and level of detail of the model used for the evaluation. NR: non-renewable, DHW: domestic hot water, bldg: building, GHG: greenhouse gas.

The main data sources and tools used to assess each indicator are annotated in Table 7-3, while the formulas for computing these values are given in Annexe 10.6. The next section further describes the evaluation process, methods, and hypotheses.


Phase 1 – Archetypes identification
Ch.4
Building stock analysis
Statistical data, GIS analysis, …
List of possible representative buildings
Arch. Def.
Archetype matching
Phase 2 – Selection and analysis of case studies
Ch.5
1
Preliminary information
Visit, old drawings, energy bills, …
2
2D drawings for the Current status scenario E0
Layout, sections and construction details
3a
Energy model | E0
Calibration with energy bills data
3b
Ener. Bills
Consumption matching
Phase 3 – Implementation of design scenarios
Ch.6
4
2D drawings for the scenarios
S0 | S1 | S2 |S3
Layout, sections and construction details
5a
Energy model
S0 | S1 | S2 | S3
BPS (LoD 3)
5b
SIA 380/1
Min. legal requirements
Thermal bridges and cond. risk
SIA 180
5c
5d
Energy model
S0 | S1 | S2 | S3
PV and BPS (LoD 3)
6
3D model
Architectural visualisations (LoD 4)
5e
Minergie 2'000W
Performance targets
Arch. Quality
Ch.7
Expert group
Workshop and online survey
7
3D model
Daylighting analysis (LoD 4)
Phase 4 – Multi-criteria assessment
Ch.7
BIPV renovation assessment tool
A
Input data
B
Pre-simulated database
PV analysis tool
b
C
Energy assessment
DIVA / EnergyPlus
Photovoltaic performance
Final energy consumption (operational phase)
D
Environmental impact analysis
KBOB / Eco-Bât
Life-cycle Analysis (LCA)
E
Cost-effectiveness analysis
EPIQR / Real examples
Life-cycle Cost (LCC)
F
Indoor comfort analysis
DIVA / EnergyPlus
Overheating
f1
Daylighting
f2
Indoor comfort
Qualitative assessment
Projects acceptability
Quantitative assessment
Performance and feasibility
Results per archetype and scenario

7.2.2. Workflows and calculation methods

This section is dedicated to the description of the proposed workflow, calculation methods, tools, reference values and assumptions used.

Global workflow

Figure 7-10 offers an overview the whole process involving the different previous phases – Phase 1 (Chapter 4), Phase 2 (Chapter 5), Phase 3 (Chapter 6) – and the one presented in this chapter, Phase 4 – Multi-criteria assessment. The schema shows the iterative processes carried out and the relations between phases to obtain the results according to the five indicator groups described in Section 7.2.1.

As shown in Figure 7-10, each component of Phase 4 (marked with A to F) provides information and data that is introduced in the BIPV renovation assessment tool, developed in the MS Excel environment. This tool allows not only to extract and visualise the results, but also to test different variants in terms of energy-use scenarios, economic parameter values, etc. It is structured based on the six main components, which are detailed below.

Input data (Part A)

The data saved here is composed of building surfaces (e.g. floor, roof, windows, façade, and BIPV elements), and reference values (e.g. interest rate, annual increase of energy cost, purchase energy cost, cost of the different renovation strategies, subsidies, energy targets, efficiency of BIPV elements). Most of the information comes from step 3b (corresponding to the analysis of the different case studies). All this information is used during the different stages of the assessment.

Pre-simulated database (Part B)

In addition to the general information in Part A (input data), a database composed of the energy simulation results obtained in steps 3b, 5b and 5e complete the input data needed to feed the BIPV renovation assessment tool. The generation of the pre-simulated database involves several steps specified in the workflow presented in Figure 7-11.

The process starts with the energy models for each archetype and design scenario (E0, S0, S1, S2 and S3) obtained during the implementation phase (Chapters 5 and 6) (1). All this information is used as input data to conduct (2a) hourly energy simulations and (2b) irradiation and photovoltaic production analyses including the active surfaces selection method described in Section 7.2.4. These results serve to define the three different comparative energy-use scenarios, described in Section 7.2.3.

Hourly simulation data, in the form of .csv (coma separated values) files, are introduced in the PV analysis tool (developed during this thesis) (3). (4) Users can analyse, visualise and extract data for the different design scenarios (E0, S0, S1, S2 and S3), HVAC system variants (oil/gas-boiler or heat-pump) and energy-use scenarios (A-100%, B-Selection, C-Batteries) to be introduced into the BIPV renovation assessment tool, where we conduct the most part of the quantitative multi-criteria assessment (5).

Figure 7-10. Global workflow linking the different phases of the methodology.

The energy simulation procedure (step 2a) has already been introduced in Chapter 5 (for the creation of the calibrated energy model corresponding to E0-Current status) and Chapter 6 (for the implementation of the design scenarios S0-S3). We here restate the main elements of our approach and provide complimentary information. The energy simulations are carried out using DesignBuilder **[DesignBuilder 2018]**, a dynamic building performance simulation software based on the EnergyPlus® simulation engine **[DOE 2018]**. The weather file (.epw) with hourly climate data of Neuchâtel, obtained from Meteonorm **[Meteotest 2018]**, is used in the simulation. The data used for configuring the energy models (e.g. U-values), including the different assumptions (e.g. occupancy, set-points) are given in Chapters 5 and 6 and Annexes 10.1 and 10.2. A detailed analysis of the thermal bridges (taken into account in the energy simulations), including the verification of the risk of condensation and mould, is presented in Annexe 10.1.

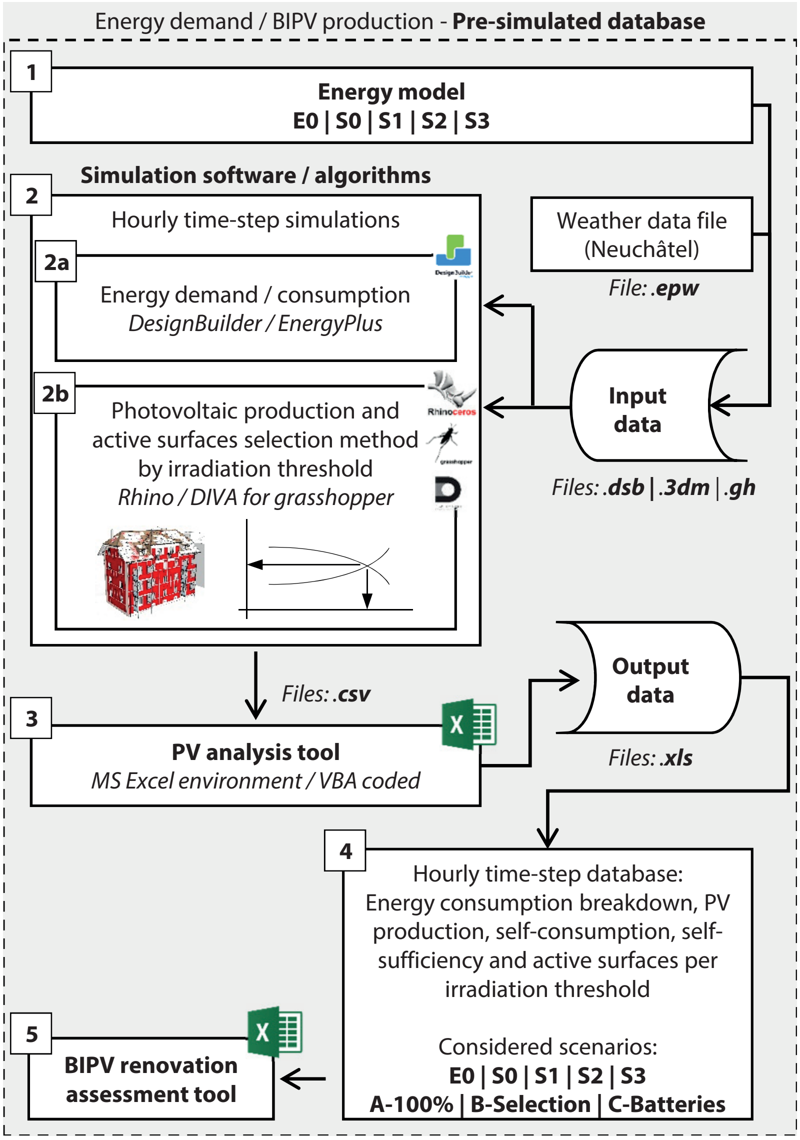


Figure 7-11. Workflow (Part B of global workflow) for the creation of pre-simulated database with hourly time-step energy demand, consumption, PV production, self-consumption, self-sufficiency, and the active surfaces per irradiation threshold for each renovation archetypes.

As mentioned, the calibrated energy model for E0 is used as a basis for constructing the models for the S0-S3 scenarios. The calibration procedure of the model basically consists in manually adapting parameters for which we do not have the exact information by following reference values obtained from the literature. The parameters that we adapt are the global performance of the HVAC system and the infiltration rate, as described below.

For defining the Coefficient of Performance (COP) of the central heating installation (common for all case studies) composed by production, distribution, emission and regulation losses, we take into account the values presented in Table 7-4 **[UCL 2018]**.

Type of installation	Partial COP [%]				Global COP [%]
	Production	Distribution	Emission	Regulation	
Very old boiler oversized or very inefficient, long distribution loop (60s-70s)					
	75-80	80-85	90-95	85-90	**46-58**
Old boiler well dimensioned, short distribution loop (70s-80s)					
	80-85	90-95	95	90	**62-69**
High efficiency boiler, short distribution loop, insulated back radiators, external sensor regulation, thermostatic valves (1990s and early 2000s)					
	90-93	95	95-98	95	**77-82**
Current condensing oil boiler, well sized (after 2000)					
	97-98	95	95-98	95	**83-87**
Current condensing gas boiler, well sized (after 2000)					
	101-103	95	95-98	95	**87-91**

Table 7-4. Global Coefficient of Performance of different central heating installations **[UCL 2018]**.

The final values adopted for the COP are presented in Table 7-5 and are based on the recommendations of SIA 380/1:2016 **[SIA 2016e]** and 10-15% of losses due to distribution, emission and regulation, as proposed in **[UCL 2018]**. For all archetypes, the oil/gas-boiler was already substituted by a more recent one and in general the distribution loop was reasonably insulated.

	Oil-boiler	Gas-boiler	Air-water Heat-Pump
COP (heating)	0.85	0.93	3.00
COP (DHW)	0.66	0.73	2.73

Table 7-5. Coefficient of Performance of the different HVAC systems, based on **[SIA 2016e]**.

Values related to the natural ventilation and uncontrolled infiltration through the building envelope (e.g. window frames) are set using as reference the SIA 180:2014 **[SIA 2014]**, which defines minimum requirements in terms of indoor comfort conditions and fixes the airtightness targets for renovation (Table 7-6).

Type of ventilation system	$m^3/h{\cdot}m^2$	Air changer per hour (ACH)
Natural ventilation	3.6	1.44
Mechanical ventilation	2.4	0.96

Table 7-6. Airtightness targets for renovation projects according to **[SIA 2014]** with a pressure difference of 50 Pa.

To reflect the building envelope performance, a different airtightness value is adopted for each scenario, going from 1.5-2.0 ACH (for the E0-Current status of the building, see Chapter 5) to 0.5-0.7 ACH (for the S3-Transformation scenario, see Chapter 6).

Energy assessment (Part C)

In Part C, the photovoltaic performance and the energy assessment for the operational phase of the building is conducted, including both a final energy balance and the environmental impact related to this energy consumption. To calculate all indicators, we use the simulation results stored in the pre-simulated database (Part B) and the input data from Part A, especially the energy cost and the environmental impact of the energy sources, shown in Table 7-7. Even though simulations have been carried out with an hourly time-step (Part B), the data used in this part are expressed on an annual basis in order to carry out the assessment for a 60-year life-cycle period.

	Units	Electricity	Oil	Natural gas
Cost	CHF/kWh	0.25	0.10	
CED	kWhPE/kWhFE	3.008	1.239	1.064
CEDnr	kWhPE/kWhFE	2.252	1.230	1.060
GWP	kWhEF/kgCO_2eq	0.102	0.301	0.228

Table 7-7. Cost and conversion factors for different energy sources. CED: Cumulative Energy demand; CEDnr: Non-renewable Cumulative Energy demand; GWP: Global warming potential **[KBOB 2016]**.

Environmental impact analysis (Part D)

The LCA is conducted using data from (A) input data, (B) pre-simulated database and (C) energy assessment, and is based on the simplified methodology proposed by the SIA 2032 [**SIA 2010**] and the SIA 2040 [**SIA 2017b**], illustrated in Figure 7-12.

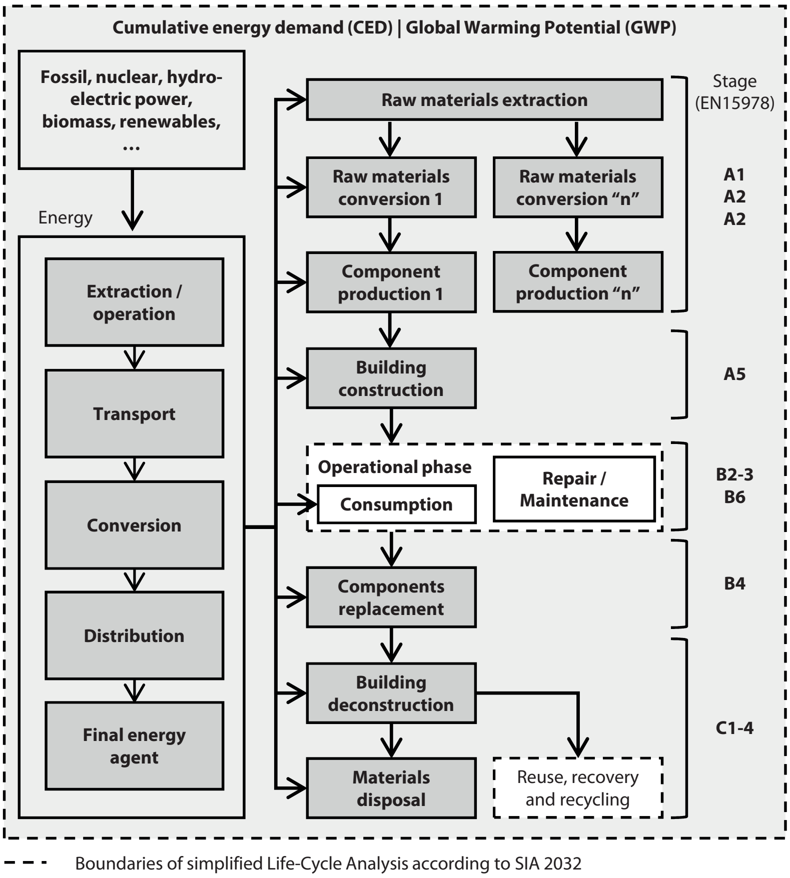


Figure 7-12. Adopted method for the simplified Life-Cycle Analysis of the renovation projects according to SIA 2032 [**SIA 2010**] and SIA 2040 [**SIA 2017a**] and the corresponding stages defined in EN 15978 [**ECS 2011**].

The objective is to calculate the environmental impact of the construction phase of the project using two main indicators CEDnr and GWP, allowing to compare results to the 2'000-Watt Society targets.

With respect to the stages described in the EN 15978 standard [**ECS 2011**], the SIA 2032 methodology does not take into account the following stages: A4 (transport to the construction site), B2 (maintenance), B3 (repair), B7 (operational water use) and D (reuse, recovery, recycling) (see also Figure 3-24, Chapter 3). To evaluate the different renovation projects, data on the environmental impacts of construction materials are obtained from the ECO-BAT software [**Citherlet et al. 2016**], following LCA standards [**ISO 2006a, 2006b; ECS 2011**] and using values adapted for the Swiss contexts from KBOB **[KBOB 2016]**, based on Ecoinvent **[ecoinvent 2018]**. The impacts of the operational phase, related to the consumption of the building, are obtained by converting the final energy consumption from the energy assessment (Part C of the global workflow) into CED and GWP using conversion factors from the KBOB database **[KBOB 2016]**. The complete list of values used are presented in Annexe 10.4.

Cost-effectiveness analysis (Part E)

In this part, we conduct the economic assessment of each scenario using the discounted cash-flow (DCF) methodology and a life-cycle approach **[SIA 2016c]**.

Price in the Canton of Neuchâtel are of 0.10 CHF/kWh (for heating oil and gas) **[Viteos 2018]** and of 0.22-0.28 CHF/kWh (for electricity), tax included **[ElCom 2018a]**. The exact electricity cost depends on the consumption category, defined by the household size and the type of appliances **[ElCom 2018b]**. For our calculations, we adopt a mean price of 0.25 CHF/kWh. We assume an energy inflation rate (annual increase in energy cost) of 2.5%, with the initial cost fixed to current values in Switzerland (these values can be changed by the user).

The Net Present Value (NPV), the Internal Rate of Return (IRR) and the payback time (PBT) are calculated using the DCF methodology for a 30-year calculation horizon with a discounted rate of 3% **[Zammit et al. 2017; DL 2018; Passer et al. 2018]**, considering the real-time self-consumption with or without battery systems and the injected electricity overproduction depending on the chosen energy-use variant.

Subsidies taken into account for the improvement of the building envelope are:

- Subsidy from the *"Programme Bâtiment"* for thermal insulation measures **[EnDK 2018b]**.
- Additional aid from the Neuchâtel commune (+15% bonus on top of the *"Programme Bâtiment"*) **[Ville de Neuchâtel 2018]**.

Subsidies considered for the photovoltaic installations are:

- Current feed-in-tariff of (0.1096 CHF/kWh) (7.7% VAT included) **[VESE 2018]** with an annual decrease of 5%/year.
- Investment aid *"Retribution Unique (RU)"* **[OFEN 2018c; pronovo 2018]**.
- Additional aid from the Neuchâtel commune of 500 CHF/kWp with a maximum of 10'000 CHF per installation **[Ville de Neuchâtel 2018]**.
- Tax reductions of 11-13% for the investment in solar installations (considering an annual revenue of 100'000 CHF with a 25% tax rate) **[OFEN et al. 2018]**.

The global cost includes the envelope renovation, the BIPV installation and a renovation of bathrooms and kitchens using reference values from real renovations examples (as typically done when a renovation process is launched). The renovation cost is obtained using reference values from real renovation projects and the EPIQR tool **[Flourentzos et al. 2000]**, developed to perform the diagnosis of existing buildings and to test different renewal scenarios. In addition, we use the Batilog DEVIS software **[BEC Partners SA 2018]** that relies on databases available for the Swiss context **[CRB 2012c, 2012b, 2012d; OFS 2015b]** based on the eCCC-Bât (Construction Cost Codes for Buildings) **[CRB 2012c, 2012b]**.

As highlighted previously, one of the main concerns about BIPV installations is related to the economic and financial aspects. As **[Yang et al. 2016]** indicate, there is a lack of detailed data about BIPV cost mainly because of the rapid evolution of the sector. To address this and obtain the most reliable data as possible both for BIPV installation and maintenance costs, a parametrisation study was done based on prices from a recent market study **[OFEN 2016b]** and a web tool **[OFEN et al. 2018]**, and taking into account economies of scale. These prices represent mean values over real costs, estimated to vary by +/- 10% **[OFEN 2016b]**. The obtained data was treated to obtain a series of curves (Figure 7-13) allowing to use the cost value parametrically in function of the active surface finally selected. The cost includes all components of the installation (PV panels, junction box, connections, cabling and inverters).

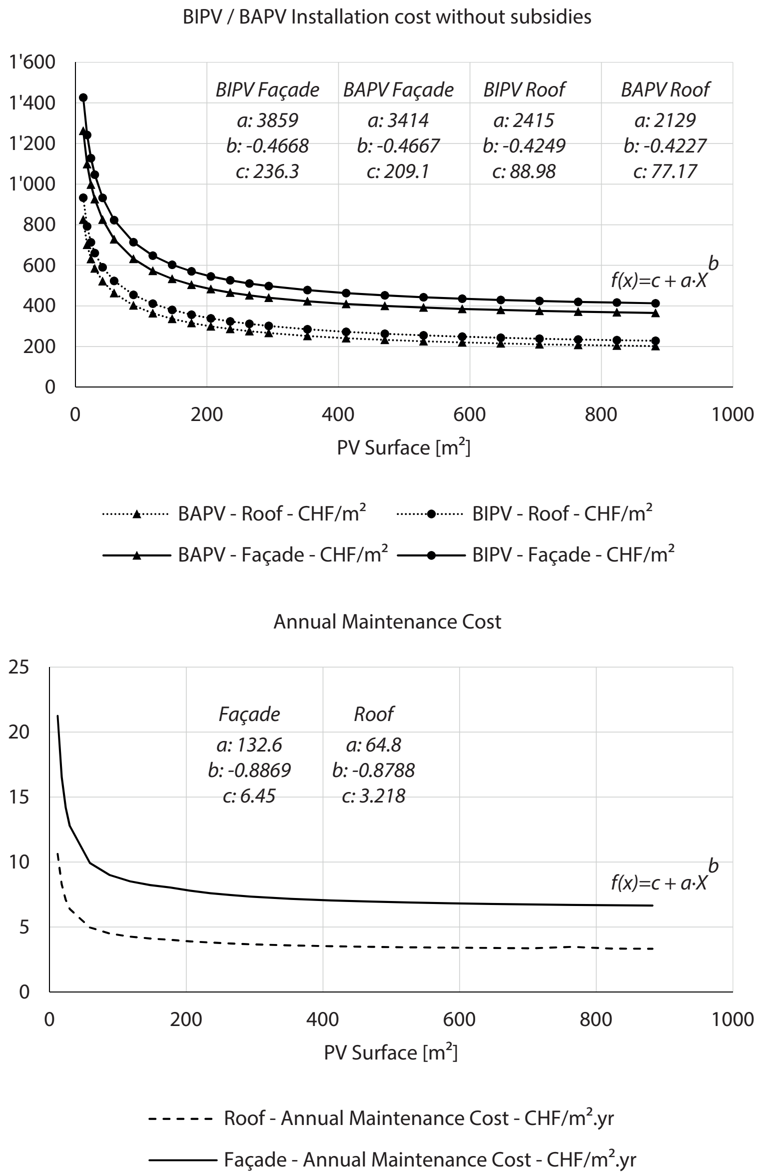


Figure 7-13. Parametrisation (curve fitting with R2 = 0.998) of the photovoltaic BIPV / BAPV installation balance of system (BOS) cost and the annual O&M (operational and maintenance) cost. Prices include all components of the installation (PV panels, junction box, connections, cabling and inverters) **[OFEN 2016b; Suisse Energie 2017; OFEN et al. 2018]**.

Regarding batteries, the prices of batteries based on lithium-ion technology proposed by some manufacturers is below 500 USD/kWh, and the expectation for 2027-2040 are prices between 175 and 340 USD/kWh for stationary and battery packs systems respectively **[Deign 2017]**. This thesis takes into account current prices of a typical 12V lithium-ion battery already on the market , assuming a mean price of 298 CHF/kWh of capacity including inverter (CC to AC) **[Swiss-green 2018]**.

Whereas results for each LCC indicator are presented in Section 7.3, detailed costs (with / without BIPV) for each scenario of each archetype can be found in Annexe 10.5.

Indoor comfort analysis | Overeating risk evaluation (Part f1)

In order to check the overheating risk due to the increase of the building envelope insulation, an independent workflow is proposed (Figure 7-14) corresponding to Part f1 in the global workflow (Figure 7-10).

Using the DesignBuilder energy models (1), we extract the hourly indoor temperature values for each renovation scenario (.csv exchange file) (2). In a MS Excel environment, an analysis of indoor temperature is conducted (3) to obtain the number of hours over the year when the temperature is higher than 26.5°C (4). This data is introduced in the BIPV renovation assessment tool (5).

The method used to calculate the overheating risk is exposed in the SIA 180:2014 standard **[SIA 2014]**, consisting in an hourly time-step simulation without any cooling system. This assessment allows verifying if the overheating limit of maximum 100 hours/year with indoor temperature above 26.5°C (fixed by **[SIA 2014]**) is respected.

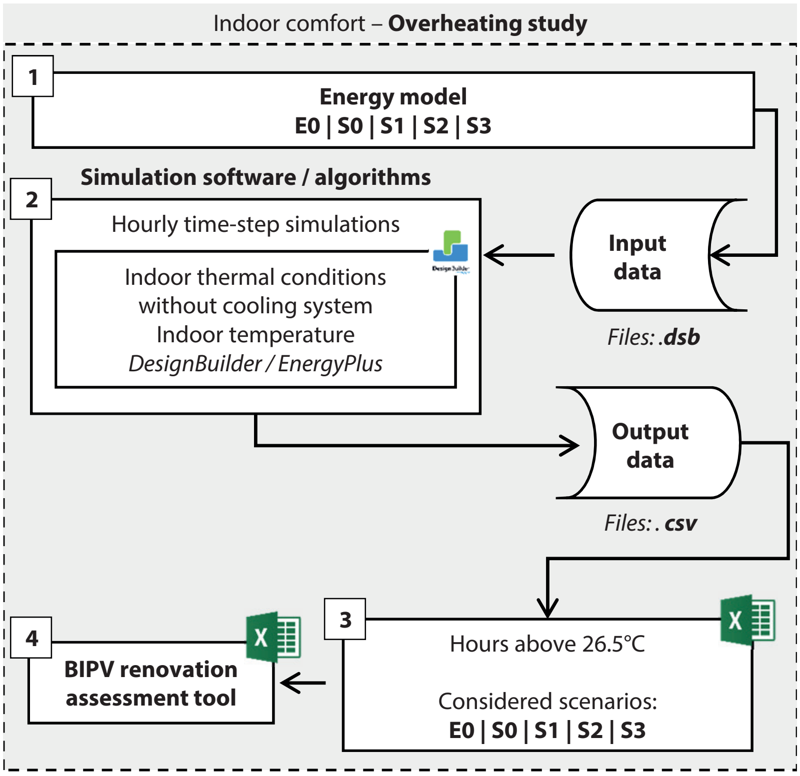


Figure 7-14. Workflow of overheating study (corresponding to Part f1 of global workflow).

Indoor comfort analysis | Daylighting potential evaluation (Part f2)

The impact of each scenario on the daylight potential is verified through the independent workflow shown in Figure 7-15, which corresponds to Part f2 on the global workflow (Figure 7-10).

The input (1) is the energy model at LoD 4 (with interior partitions) that complies with all performance and qualitative aspects. The daylighting analysis is conducted (2) using DIVA **[Solemma LCC 2018]** for Rhino **[Robert McNeel & Associates 2018]** as further detailed below. From this process, a MS Excel file (.xls) with the results is generated and (3) introduced in the BIPV renovation assessment tool (4).

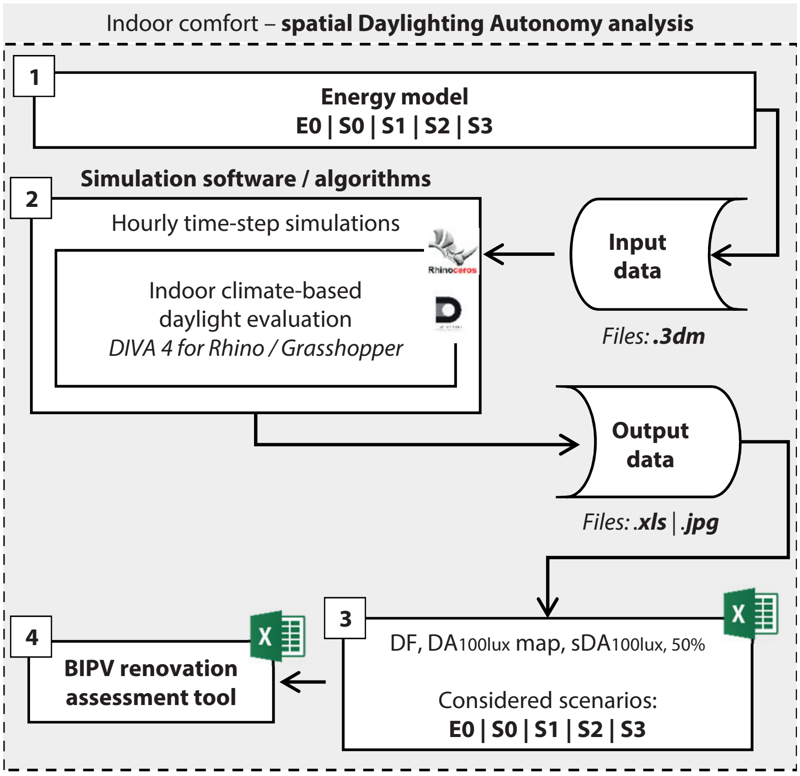


Figure 7-15. Workflow of the daylighting study (corresponding to Part f2 of global workflow)..

As seen in the previous chapter, our renovation strategies include increasing the façade thickness, by adding insulation, and replacing windows with high-performance glazing that have lower thermal and visual transmittance. These interventions have counteracting effects. On the one hand, they contribute to increasing the energy efficiency by reducing thermal exchanges with the exterior environment and thus heating demand and overheating risk. On the other hand, they can also increase energy demand for heating and artificial lighting since they allow less heat and natural light to enter the building **[Lolli et al. 2017]**. The side on which the energy balance will tip – i.e. whether the decrease will counterbalance the increase – depends on the specificities of the building (climate, occupancy, etc.) and the types of intervention. However, in the case of the renovation of residential buildings, given the lower window-to-wall ratio (below 0.3 in our case studies) compared to modern highly-glazed office buildings, the energy efficiency gains are likely to dominate. This was the result obtained by **[Lolli et al. 2017]**, who looked at the influence of replacing windows on the energy use for space heating and electric lighting for three residential buildings in Norway. They found that the energy saving for space heating largely compensated the increase in lighting electricity use.

However, low daylighting levels can also negatively affect human health and well-being [**Ámundadottir 2016**]. To assess the daylight performance of a space, different evaluation metrics have been proposed. One such metric is the Daylight Factor (DF), computed as the ratio between the internal illuminance and the horizontal illuminance in an unobstructed situation (e.g. outdoor) under standard overcast sky conditions defined by the International Commission on Illumination (CIE), corresponding to having no sun [**Mardaljevic et al. 2011**]. A DF value of at least 2% is typically recommended [**Carrier et al. 2000**]. Although widespread, this simple metric is insensitive to building orientation and location (climate) [**Mardaljevic et al. 2011**]. As such, daylight metrics have more recently evolved towards more dynamic, climate-based metrics such as the Daylight Autonomy (DA), capable of capturing the variability of daylight availability [**Mardaljevic et al. 2011; IES 2013**]. The DA is a temporal metric computed at different points on a horizontal plane (typically about 0.8 m above the floor level), that provides the percentage of occupied hours over the year when a specific illuminance value (e.g. 300 lux) is reached. From that map of values can be computed the spatial Daylight Autonomy (sDA), a spatial descriptor of the annual sufficiency of ambient daylight levels [**IES 2013**]. The sDA corresponds to the percentage of the space that has a DA above or equal to 50%, that is, that receives over or equal to the lux setpoint (e.g. 300 lux) at least 50% of the occupied hours over the year. It is noted as sDAX/50%, where X is the user-defined illuminance level (in lux). For reference, [**IES 2013**] defines a *"nominally accepted daylight sufficiency"* of sDA300/50% = 55%.

Lighting conditions required within residential spaces vary as much as the tasks and activities that may be conducted within those spaces. They also depend, among others, on the inhabitants' age and occupancy profiles [**DiLaura et al. 2014**]. As such, recommended illuminance values for residential buildings also vary significantly in the literature. The IESNA specifies distinct values per space, such as 100 lux for bedrooms, bathrooms, and living rooms, and 300 lux for performing tasks like cooking, laundry or reading [**Dogan et al. 2018**]. Similarly, the CIBSE recommends 150 lux in dining halls and kitchens, and 100 lux in bedrooms and toilets [**Caple 2016**]. A lower value of 50 lux is given in [**SIA 2015a**] for collective housing buildings and in [**NREL 2009**] for residences in general.

In light of these recommendations, we have chosen a 100-lux target illuminance for all spaces within the apartments. The analysis is conducted over the occupied daytime hours (7-18h), corresponding to 4015 hours over the year. The DA is simulated using the DIVA [**Solemma LCC 2018**] plug-in for Rhino [**Robert McNeel & Associates 2018**] that uses the Daysim calculation engine [**Reinhart 2018**]. The analysis is done over a grid of sensors covering all interior spaces except circulation zones, as can be seen in Figure 7-16. The sensors are separated by 0.45 m and located 0.76 m above the floor level. The number of ambient bounces, corresponding to the maximum number of diffuse bounces in the indirect radiation computation [**Ward 1996**], was set to a recommended value of six [**Ibarra et al. 2009**]. Materials for opaque / glazed surfaces are selected from the software library (containing Radiance [**Ward et al. 1998**] material descriptions) and have the following reflectance / transmittance values: 35% for balconies and external façade, 80% for the ceiling, 20% for the floor and outside ground, 70% for interior walls and partitions, 80% for windows. No electric lighting and shading control systems are simulated.

The DIVA software provides the simulation results (shown in the results section) in the form of DA maps and a Daylit Area indicator that essentially corresponds to the sDA described above (sDA100lux,50%). The more commonly known DF is also shown in the results section.

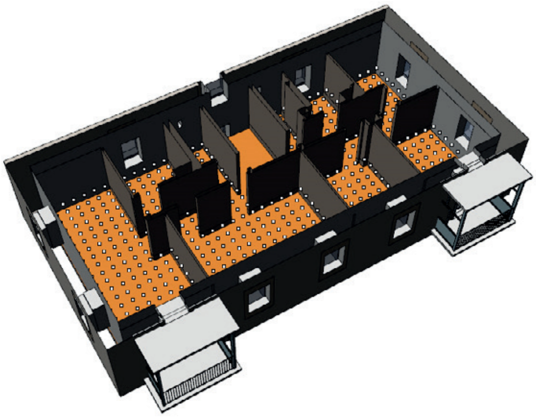


Figure 7-16. View of the detailed model and grid of sensors for the daylighting study. Example shown for Archetype 1, scenario S3.

BIPV renovation assessment prototype tool

This section shows screenshots of the prototype tool – referred to as the BIPV renovation assessment tool in the global workflow – coded in the MS Excel environment (VBA). The tool contains multiple functionalities that enable a user to modify some of the assumptions (e.g. economic values such as interest rate and energy prices) and update the corresponding results shown in table and graph formats. It is also possible to compare different scenarios, not only with respect to the options previously defined (e.g. A-100%, B-Selection, C-Batteries, with/without injection, etc.), but also additional variations such as the activation or not of surfaces (for instance to compare the actual BIPV scenarios to a version where all of its currently active surfaces are instead non-active dummy panels).

Out of the various possible functionalities and options offered by the tool, results for the ones more closely related to the main objectives of the research are included in this thesis, also for conciseness reasons. The following Figure 7-17 and Figure 7-18 illustrate screenshots of the tool.

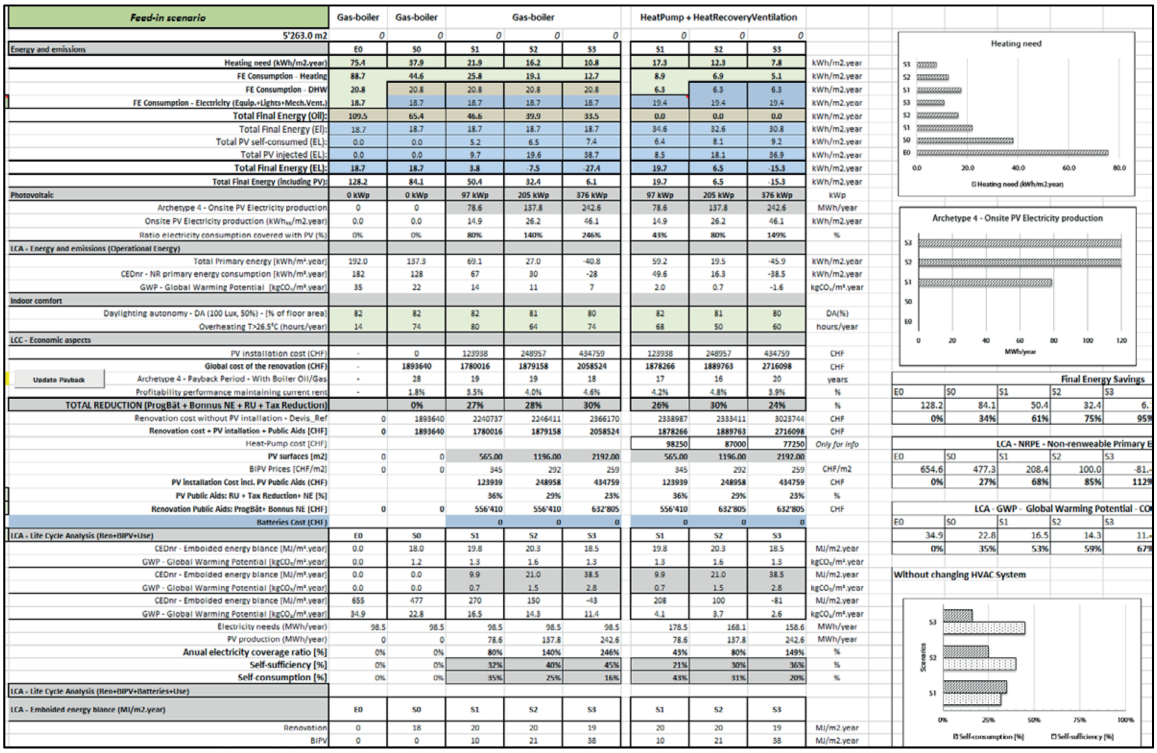


Figure 7-17. BIPV renovation assessment tool – Screenshot of the LCA tab showing annual results.

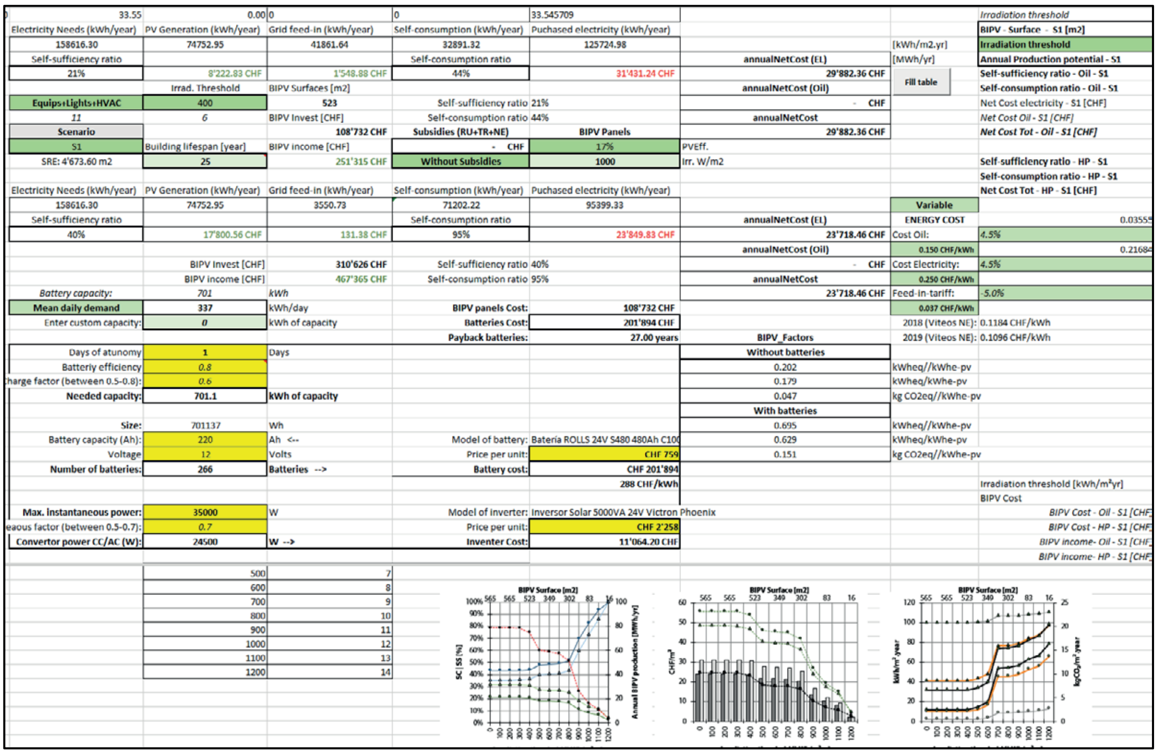


Figure 7-18. BIPV renovation assessment tool – Screenshot of the PV Analysis tool showing, among others, the active surfaces selection and economic viability results.

7.2.3. Comparative energy-use scenarios

As introduced in Chapter 6 (Section 6.2.3), for each design scenario, three energy-use scenarios (Figure 7-19) related to the sizing of the BIPV installation and the implementation of storage systems are considered. These scenarios are here described and relate to part B of the global workflow (Figure 7-10) and more specifically step 4 of Figure 7-11.

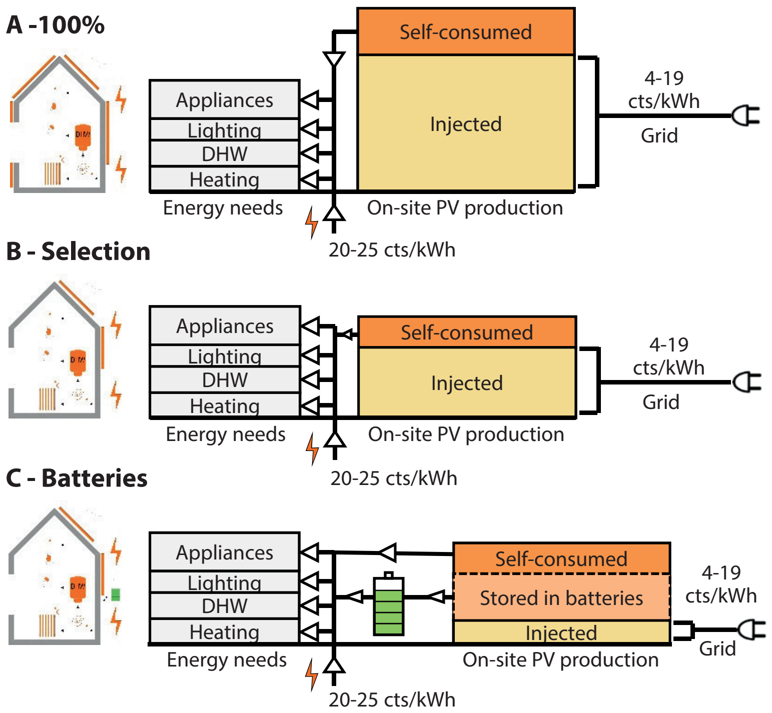


Figure 7-19. Comparative energy-use scenarios with energy balance according to **[SIA 2015b]**.

A-100%: Takes into account the activation of 100% of the possible surfaces detected during the implementation of each renovation scenario (described and shown in Chapter 6). The 100% thus refers to the whole of the previously identified potentially active surfaces and not to the entire building envelope. This scenario indicates the maximum electricity production potential (relative to the potentially active surfaces) and is interesting as a basis to which compare the other scenarios below.

B-Selection: Takes into account only a selection of the possible active surfaces (portion of what is in A-100%) that leads to a trade-off between self-consumption and self-sufficiency, resulting in a more reasonable installation, better adapted to the demand of the building. The rest of the possible active surfaces present the same visual aspect, but without PV cells. The selection is done through the active surfaces selection method described below in Section 7.2.4, where the sizing technique is further motivated and explained.

C-Batteries: Taking into account the same selection conducted in scenario B, a battery system is implemented in order to increase the self-consumption and self-sufficiency of the building.

The calculation of the PV electricity production including assumptions and tools used is described in the next Section 7.2.4.

Regarding batteries, we consider a variable lifetime depending on the level of utilisation, counting the amount of energy that could transit (in and out) through the battery. Typical values are used corresponding to lithium-ion batteries – a mature technology – with an approximated 5'000 cycles (charge-discharge) of lifespan. This number of cycles does not mean that batteries are then useless, but rather that their storage capacity is reduced to 80%. Other assumptions for calculation are a depth of discharge (DoD) of 90% and a battery efficiency of 80% (round-trip efficiency) **[Stenzel et al. 2014; Vandepaer et al. 2017; Swiss-green 2018]**. Depending on the utilisation level (energy-use scenario) and the total capacity of the battery, the expected lifetime can vary between 5 to 20 years. We here use stationary batteries to check what could be the influence of a storage system both in terms of energy balance and environmental impact, but it is also possible to use bidirectional electric vehicle (EV; with charging-discharging option) that play the same role than stationary batteries.

Figure 7-20 shows an example of the results from the economic study conducted to size the battery for each archetype when defining the energy-use scenario C-Batteries.

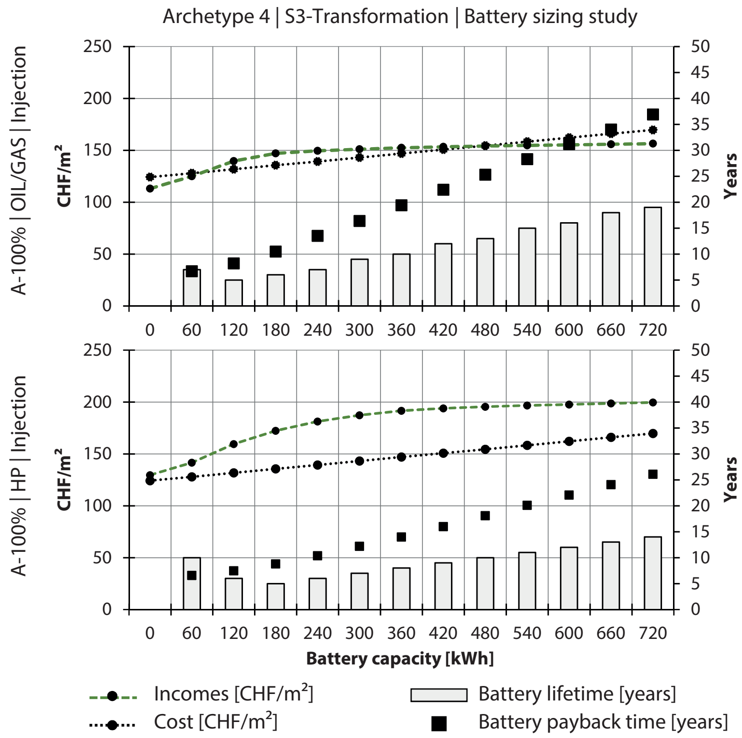


Figure 7-20. Battery sizing example for Archetype 4, considering two options of HVAC system (OIL/GAS or HP).

This study takes into account the cost of the whole installation (BIPV panels, batteries and auxiliary equipment) and the incomes obtained during a standard lifetime for PV installations of 25 years. Calculations take into account the loss of storage capacity (about 20% of loss after the expected lifespan). Incomes are composed by the equivalent cost of the electricity self-consumed (using 0.25 CHF/kWh) and the electricity injected into the grid (using a current Feed-in-tariff of 0.037 CHF/kWh). Formulas are shown in Annexe 10.6.

For this example, corresponding to the Archetype 4 (S3-Transformation), the range of capacities recommended when the existing oil-boiler is maintained is of 120-360 kWh (with an optimum value of about 180 kWh corresponding to the maximum difference between incomes and cost). If the oil-boiler is replaced by a heat-pump, a larger range of capacities is recommended. In this case, all simulated capacities become cost-effective, but the optimum values are between 300 and 480 kWh of capacity.

Conducting this study for each archetype and scenario leads to the final conclusion that the recommended values correspond approximately to a mean daily need for electricity. The energy-use scenario C-Batteries is therefore defined by automatically sizing the capacity of the battery for a mean consumption day of autonomy. As shown in Section 7.3.4, the battery capacity for the Archetype 4 (S3-Transformation) is fixed at 323 kWh (with oil-boiler) and 435 kWh (with heat-pump), corresponding to a mean electricity demand of 233 and 313 kWh/day respectively.

In addition to the three energy-use scenarios A-100%, B-Selection, and C-Batteries, two options are compared regarding the way in which to use the energy produced by the BIPV installation:

Injection (Feed-in-tariff): This approach allows for the possibility of injecting the electricity overproduction into the grid in exchange of a feed-in-tariff fixed by the local electricity supplier (Viteos in the case of Neuchâtel). With respect to Figure 7-19, both the self-consumed (orange) and injected (yellow) parts are therefore considered.

No-injection (Self-consumption): This approach assumes that it is not possible to inject the overproduced PV electricity into the grid, in order to avoid problems related to having a massive number of electricity-producing buildings injecting into the grid. This approach projects us in a future where it is necessary to maximise the self-consumption potential by sizing the PV installation in accordance to the energy needs of the building. With respect to Figure 7-19, only the self-consumed (orange) part is therefore considered.

The above variations in the energy-use and injection possibilities are applied to each BIPV renovation scenario, in their twofold HVAC system configurations: 1) maintaining the existing HVAC system (oil- or gas-boiler) and 2) changing the existing HVAC system by an Air-water heat-pump (HP) system in order to increase the self-consumption potential (by using the electricity produced by the active elements towards heating and DHW needs).

Figure 7-21 summarises the set of scenarios and variants assessed.

Summary of scenarios and variants studied

<table>
<tr><th></th><th>Current</th><th>Baseline</th><th colspan="3">BIPV</th></tr>
<tr><th>Design Scenario</th><th>E0</th><th>S0</th><th>S1</th><th>S2</th><th>S3</th></tr>
<tr><td>HVAC</td><td colspan="2">OIL/GAS</td><td colspan="3">OIL/GAS | HP</td></tr>
<tr><td>Energy-use</td><td></td><td></td><td colspan="3">A-100% | B-Selection | C-Batteries</td></tr>
<tr><td>Grid</td><td></td><td></td><td colspan="3">Injection | No-injection</td></tr>
</table>

Figure 7-21. Summary of scenarios and variants studied.

7.2.4. Active surfaces selection method

This section describes the method developed to select the building surfaces to be rendered active for the energy-use scenario B-Selection (described in the previous section). This selection process occurs in part B of the global workflow (Figure 7-10) and more specifically at step 2b of Figure 7-11. An article detailing this new method is published [**Aguacil et al. 2019**].

As seen in Chapter 3 (Sections 3.2.3 and 3.3.2), to select the building surfaces where PV panels could be placed, a common technique consists in relying on a minimum irradiation value used as a threshold. Until now, using a BAPV approach and given the relatively high prices of PV elements, a minimum irradiation threshold from which to install a panel was motivated mainly by economic profitability. The use of these thresholds can however prevent the implementation of BIPV elements on building façades [**Fath et al. 2015**]. In addition, as previously discussed, the market is changing rapidly and the decrease of prices, the improvement of PV efficiency and the emergence of new customisation techniques [**EIA 2017; SIONIC 2017; SolarPower Europe 2017; Zanetti et al. 2017; OFEN et al. 2018**] suggest that it is a good idea to not limit the sizing method to these high irradiation thresholds [**Costanzo et al. 2018**]. Nowadays, research focusing on the electricity-production of PV panels in low irradiation conditions [**Stamenic et al. 2004**] show that production losses, with respect to the nominal production under standard test conditions (STC) using 1’000 W/m^2 and 25°C [**Taylor 2010**], are more than reasonable. In northern latitudes like Switzerland, irradiation levels close to the STC can be achieved only when installing PV elements on the roof. However, as highlighted in [**Stamenic et al. 2004**], for irradiation levels of at least 400 kWh/m^2·year, the efficiency losses in terms of production will not exceed 20% with respect to the production under STC.

The method we here propose relies on an irradiation threshold to identify the surfaces where to install PV elements, but so as to be restrictive in terms of surfaces, the value of this threshold is varied within a certain range, as further detailed below.

Some PV sizing methods also include optimising for one or a combination of indicators such as electricity production, economic profitability, etc. Introduced in Chapter 3, two indicators that take into account the load profile of the building are the self-consumption (SC) and self-sufficiency (SS) ratios [**Luthander et al. 2015**]. The formula for calculating these indicators are presented in Annexe 10.6.2. The SC is the percentage of the PV-generated electricity that is consumed by the building, corresponding to the orange area in Figure 7-22 divided by the light-blue area (example for one day). The SS is computed by comparing the self-consumed PV-electricity to the building’s total electricity needs, i.e. the orange area with the grey area.

The SC and SS depend not only on the size of the installation and the building’s needs, but also on the temporal match between electricity production and need. The trend these indicators follow are in opposition, as can be understood from a simple example. In a situation where a small BIPV installation is applied, the SC will be high as most produced energy is self-consumed in real-time by the building (representing a good use of the BIPV installation), whereas the SS will be low since not much energy can be produced with respect to the building’s total needs. Conversely, in a situation where a large installation is applied to the same building, the SC will be low (indicating that too much energy is produced for the immediate needs of the building) and the SS higher, since the total PV electricity produced is closer to the total needs. At this point, it is important to note that this high value of SS can only be taken into account in the global energy balance if the overproduced energy can be injected into the network, otherwise the majority of the electricity produced is lost, putting in evidence the oversizing of the installation. It is therefore necessary to size the installation by finding a good compromise between SS and SC to obtain a well-adapted installation.

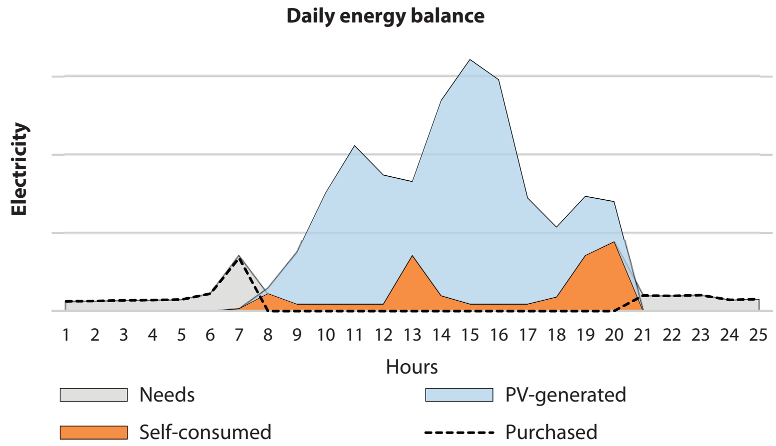


Figure 7-22. Schematic example of a daily profile in terms of hourly electricity needed by the building, PV-generated, self-consumed, and purchased from the grid.

The method therefore consists in searching for the irradiation threshold value that leads to a BIPV surface configuration for which a trade-off between SC and SS is obtained. To do so, different BIPV configurations (and associated electricity production) are generated automatically by filtering out, at each iterative irradiation threshold value (Ti), the possible active surfaces initially defined that do not reach Ti. The starting model – equivalent to the A-100% configuration – differs for each scenario (S1-S2-S3) according to the images shown in Chapter 6, where all potential surfaces have already been identified. Ti is varied from a minimum value of 0 kWh/m^2·year (all potentially active surfaces maintained) up to 1’200 kWh/m^2·year, close to the maximum available irradiation for the considered location (Neuchâtel).

The use of an irradiation threshold ensures that selected surfaces are mainly adjacent to each other, as groups or patches of surfaces with similar solar exposure naturally emerge. This results in configurations that are more realistic and feasible, for technical reasons, than if the active surfaces were scattered. The surfaces that are filtered out, e.g. façade surfaces when Ti > 1’000 kWh/m^2·year, are considered non-active panels (dummies, with the same appearance).

The filtering is done through an automated simulation-based process coded in Grasshopper **[Davidson 2018]**. At an hourly time-step, the electricity production and BIPV surface is obtained for each irradiation threshold value, using DIVA **[Solemma LCC 2018]** for the irradiation simulation and Archsim **[Dogan 2018]** for the production calculation, using a PV panel efficiency of 17% **[Cerón et al. 2013; 3S Solar Plus AG 2018]**. A 0.8% PV production decrease per year is also included **[Passer et al. 2018]**, according to the guaranteed performance of PV elements **[3S Solar Plus AG 2018]**.

The production values are used along with the hourly energy simulation results (step 2a in Figure 7-11) to calculate the SC and SS. This step takes place in the Excel PV Assessment Tool (step 3 in Figure 7-11).

Results from applying this active surfaces selection method are shown in Section 7.3 for different irradiation threshold values (depending on the archetype) in the form of false-colour images showing the corresponding active surfaces with their solar irradiation levels. The trade-off threshold value finally identified is shown through a graph illustrating the SC and SS in function of the increasing irradiation threshold value. For each scenario (S1, S2, S3), four different thresholds are obtained, depending on whether the existing boiler is maintained or replaced by a heat-pump and if a storage system is implemented (for the C-Batteries energy-use scenario).

It is important to highlight that no energy management systems on the demand side are considered in our approach. Using this kind of systems, the SC could be further increased, for example by controlling the moment when certain electrical appliances are used or by charging electric vehicles (EV) during the hours of greatest photovoltaic production and lower demand of the building. In case of residential use, this would be during the central hours of the day, and a good part of the morning (from 8 to 11h) and of the afternoon (from 14 to 17h).

As will be seen from the results, the method allows demonstrating that a larger range of irradiation thresholds (compared to what is typically encountered in the literature) should be considered for matching the building needs to improve SC and SS values, and reach cost-effectiveness given the actual prices of BIPV products. Moreover, the method represents a robust selection technique that is independent from economic parameters, and that ensures a logical grouping (as opposed to a disparate distribution) of the surfaces to be made active. From a designer point of view, this compact distribution of BIPV elements is advantageous as it makes the installation easy to implement and connect. The configurations obtained are moreover in line with the results from a simplified economic study conducted to verify the compatibility of the selection method with a viable financial situation. This study can be found in Annexe 10.3.

7.3. Results per case study

In this section are presented the results, for each case study and renovation scenario in their various variants (energy-use scenarios, etc.). The section follows the same order as the quantitative indicators presented in Section 7.2.1 (Table 7-3), with the addition of the results for the BIPV sizing following the different energy-use scenarios described in Section 7.2.3, including the results of the active surfaces selection method detailed in Section 7.2.4.

Introductory and descriptive elements, for presenting and analysing the images and graphs, that are identical for all archetypes are included in the text of Archetype 1 only and left out for the others, in order to avoid repetitions. The reader is therefore referred to Section 7.3.1 in case information was found to be missing in the subsequent sections.

7.3.1. Archetype 1

Sizing of BIPV installation

Figure 7-23 presents the results of the active surfaces selection for Archetype 1. On the left, the surfaces of the building that receive enough solar energy to be considered as active are highlighted for four irradiation thresholds. This visualisation thus indicates where the installation of active elements is advisable. The resulting active surfaces (or number of BIPV panels), the hourly on-site production and the final SC and SS values are used to build the graphs to the right of Figure 7-23 (right).

The energy-use scenario A-100% corresponds to an irradiation threshold of 0 kWh/m^2·year (first column of images on the left).

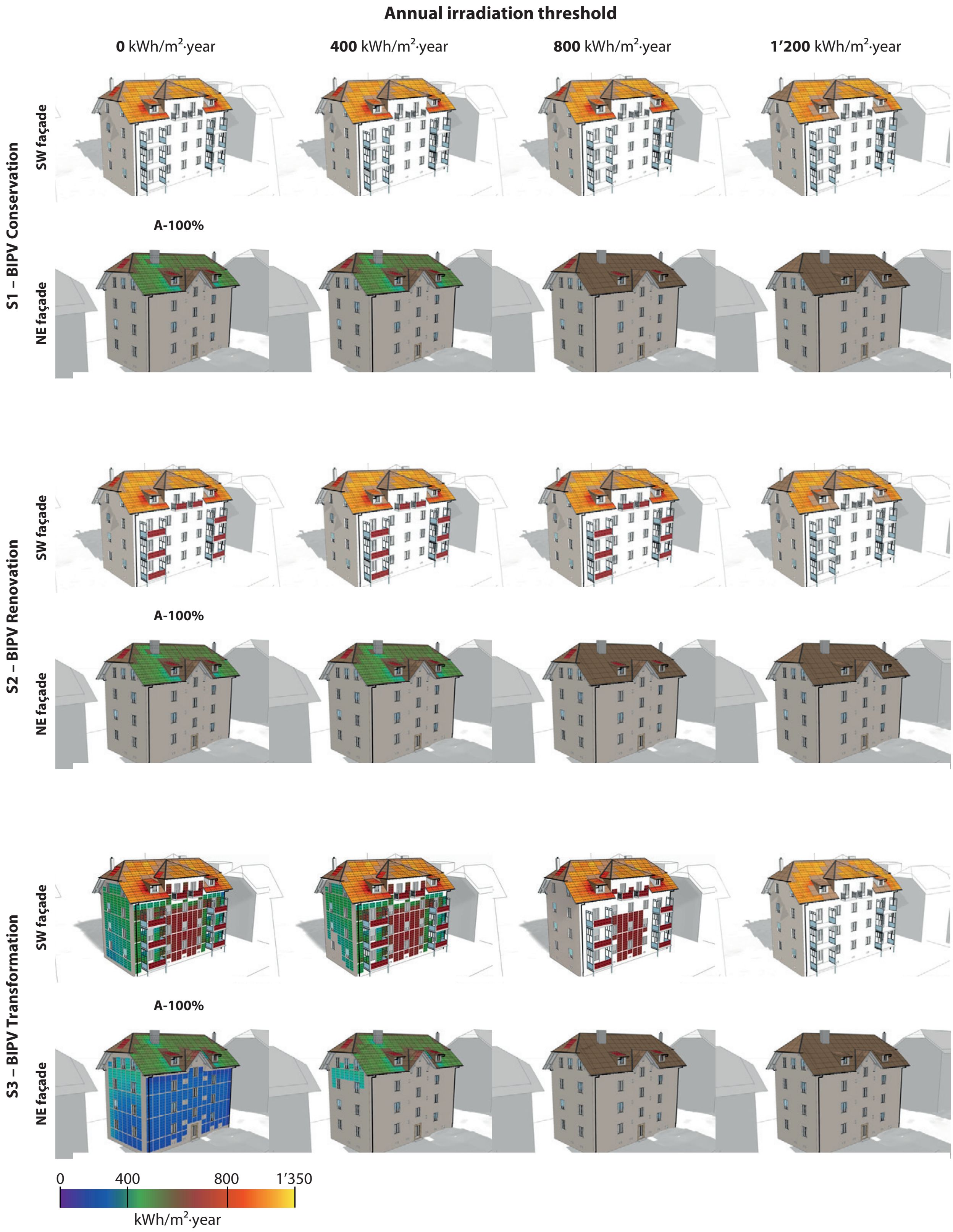
The energy-use scenario B-Selection is defined by first identifying the trade-off irradiation threshold value from the graphs on the right. We can observe that the curves representing the SC (in blue) and the SS (in green) present opposite tendencies, as explained in Section 7.2.4.

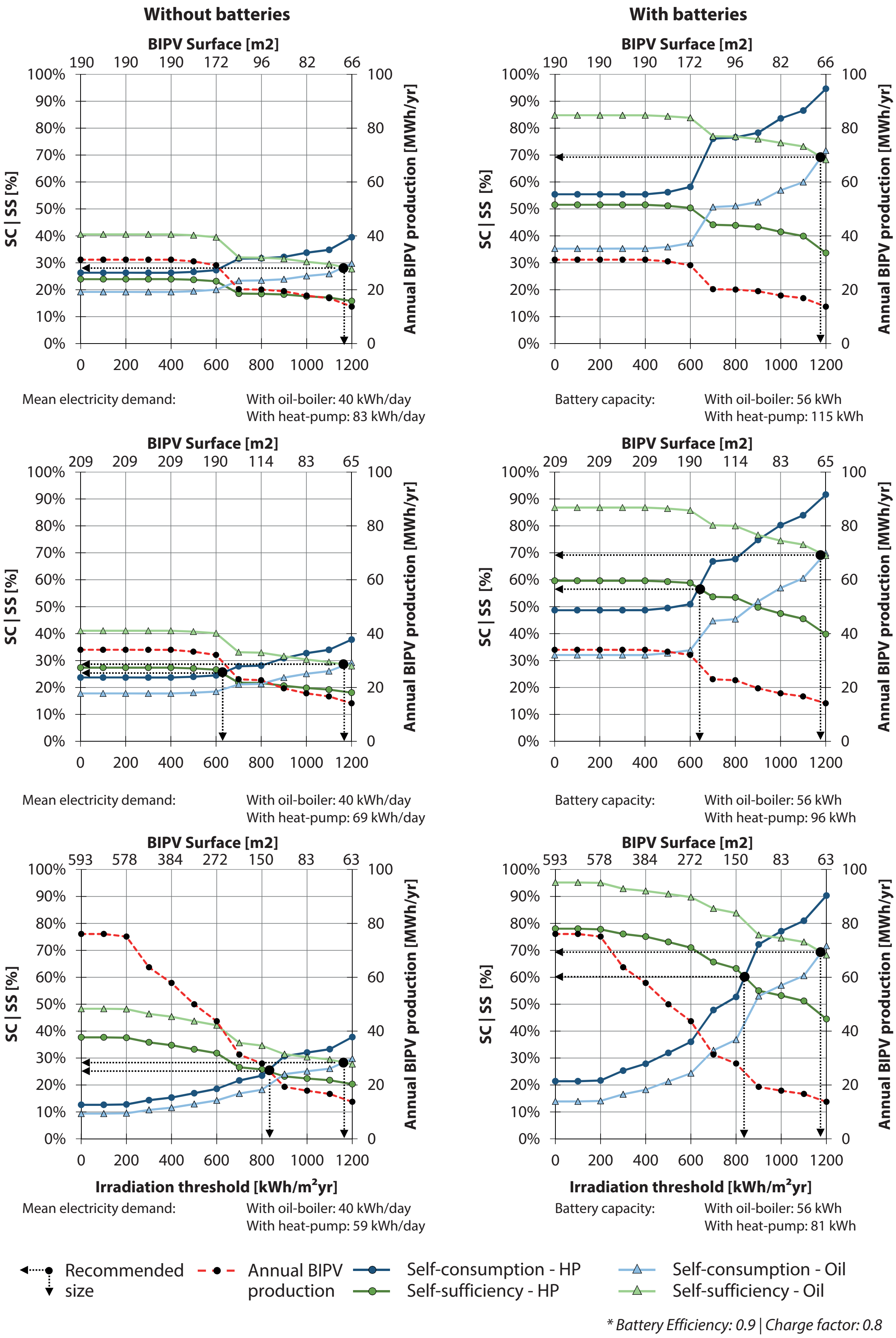
For this archetype, when the oil-boiler is maintained (both with or without batteries), the level of irradiation leading to a better equilibrium between SS and SC is of about 1’100 kWh/m^2·year, meaning that only the most exposed part of the roof should be considered.

However, if the oil-boiler is replaced by a heat-pump, the surfaces with at least 500-600 kWh/m^2·year should be considered, highlighting the importance of taking into account façade surfaces.

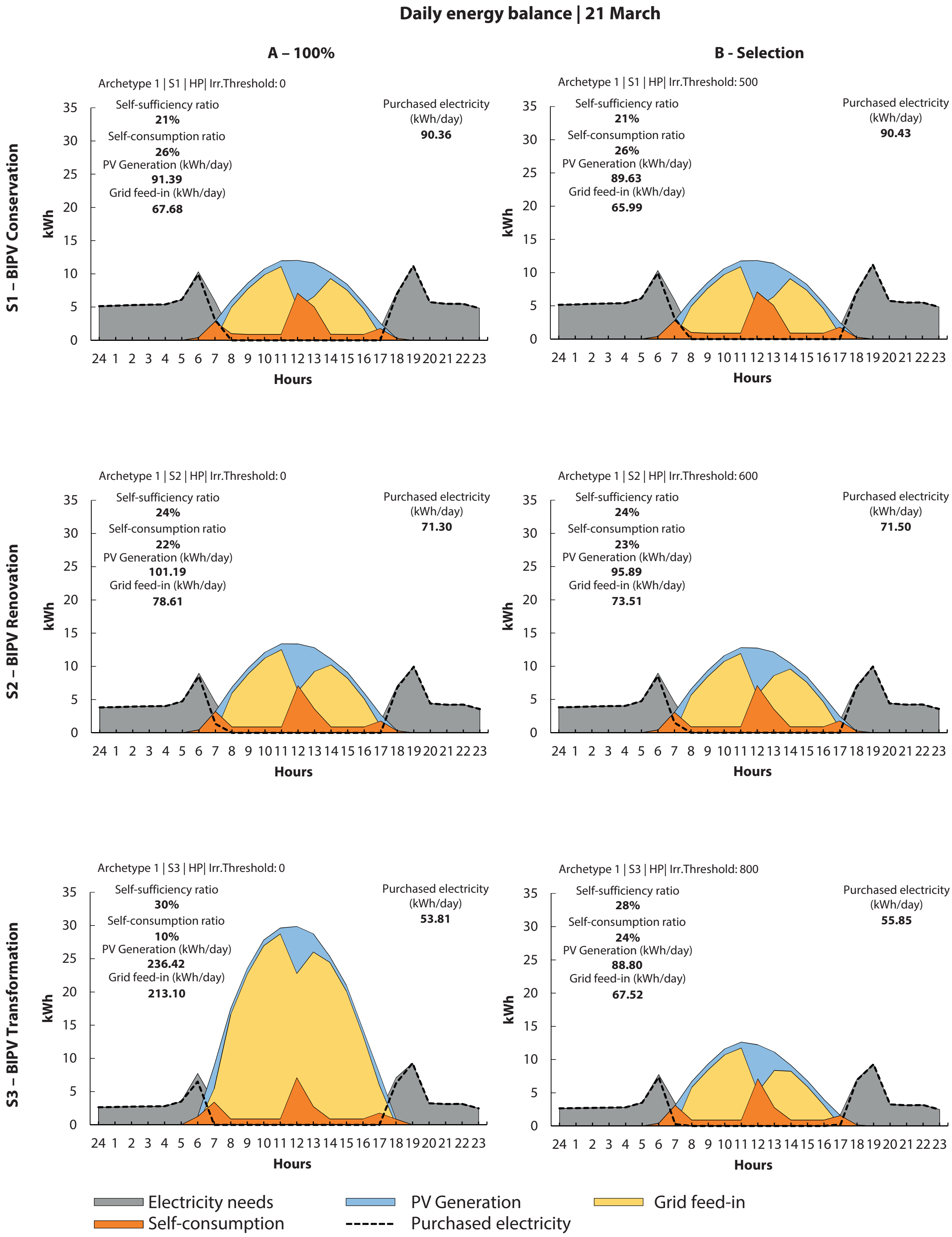
The energy-use scenario C-Batteries is obtained by integrating batteries after conducting the active surfaces selection (B-Selection). In this case, the recommended irradiation thresholds are the same, but higher levels of SC and SS between 50 and 70% are achieved. Looking at scenario S3-Transformation, the daily mean electricity demand of 40 kWh/day (oil-boiler) and 59 kWh/day (heat-pump) lead to a total battery capacity of 56 and 81 kWh respectively. If no battery system is included, the recommended threshold is about 1’100 kWh/m^2·year (oil-boiler) and 800 kWh/m^2·year (heat-pump), leading to 17 and 28 MWh/year of on-site production and 26% and 23% of SC respectively.

Naturally, the question about the economic feasibility of this approach arises. For that reason, in order to verify the consistency between an economic approach versus our approach using SS and SC to select the active surfaces and the size of the battery, a specific economic study was conducted and presented through an example in Annexe 10.3.


Annual irradiation threshold
0 kWh/m²·year
400 kWh/m²·year
800 kWh/m²·year
1’200 kWh/m²·year
S1 – BIPV Conservation
SW façade
NE façade
A-100%
S2 – BIPV Renovation
SW façade
NE façade
A-100%
S3 – BIPV Transformation
SW façade
NE façade
A-100%
0
400
800
1’350
kWh/m²·year

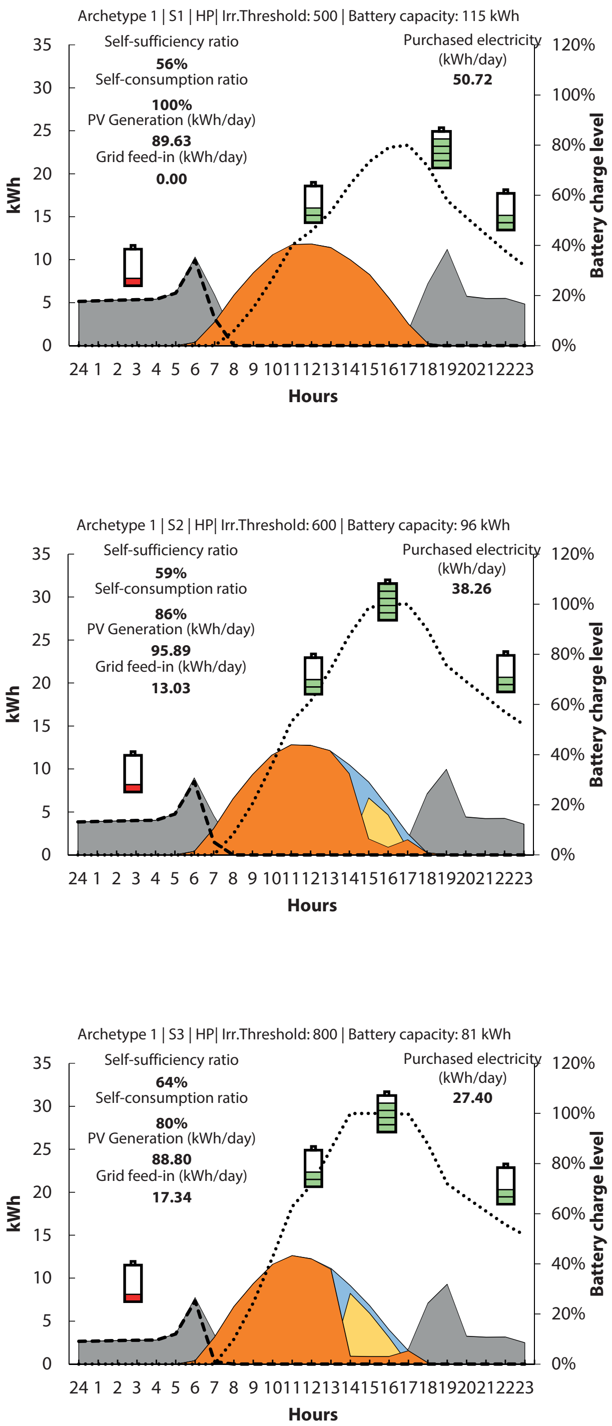


Without batteries
With batteries
BIPV Surface [m2]
190 190 190 172 96 82 66
209 209 209 190 114 83 65
593 578 384 272 150 83 63
SC | SS [%]
Annual BIPV production [MWh/yr]
0 200 400 600 800 1000 1200
Irradiation threshold [kWh/m²yr]
Mean electricity demand: With oil-boiler: 40 kWh/day With heat-pump: 83 kWh/day
Battery capacity: With oil-boiler: 56 kWh With heat-pump: 115 kWh
Mean electricity demand: With oil-boiler: 40 kWh/day With heat-pump: 69 kWh/day
Battery capacity: With oil-boiler: 56 kWh With heat-pump: 96 kWh
Mean electricity demand: With oil-boiler: 40 kWh/day With heat-pump: 59 kWh/day
Battery capacity: With oil-boiler: 56 kWh With heat-pump: 81 kWh
Recommended size
Annual BIPV production
Self-consumption - HP
Self-sufficiency - HP
Self-consumption - Oil
Self-sufficiency - Oil
* Battery Efficiency: 0.9 | Charge factor: 0.8



Daily energy balance | 21 March
A – 100%
B - Selection
S1 – BIPV Conservation
S2 – BIPV Renovation
S3 – BIPV Transformation
Archetype 1 | S1 | HP| Irr.Threshold: 0
Self-sufficiency ratio
21%
Self-consumption ratio
26%
PV Generation (kWh/day)
91.39
Grid feed-in (kWh/day)
67.68
Purchased electricity
(kWh/day)
90.36
Archetype 1 | S1 | HP| Irr.Threshold: 500
Self-sufficiency ratio
21%
Self-consumption ratio
26%
PV Generation (kWh/day)
89.63
Grid feed-in (kWh/day)
65.99
Purchased electricity
(kWh/day)
90.43
Archetype 1 | S2 | HP| Irr.Threshold: 0
Self-sufficiency ratio
24%
Self-consumption ratio
22%
PV Generation (kWh/day)
101.19
Grid feed-in (kWh/day)
78.61
Purchased electricity
(kWh/day)
71.30
Archetype 1 | S2 | HP| Irr.Threshold: 600
Self-sufficiency ratio
24%
Self-consumption ratio
23%
PV Generation (kWh/day)
95.89
Grid feed-in (kWh/day)
73.51
Purchased electricity
(kWh/day)
71.50
Archetype 1 | S3 | HP| Irr.Threshold: 0
Self-sufficiency ratio
30%
Self-consumption ratio
10%
PV Generation (kWh/day)
236.42
Grid feed-in (kWh/day)
213.10
Purchased electricity
(kWh/day)
53.81
Archetype 1 | S3 | HP| Irr.Threshold: 800
Self-sufficiency ratio
28%
Self-consumption ratio
24%
PV Generation (kWh/day)
88.80
Grid feed-in (kWh/day)
67.52
Purchased electricity
(kWh/day)
55.85
kWh
Hours
Electricity needs
Self-consumption
PV Generation
Purchased electricity
Grid feed-in

C - Batteries



It is interesting to highlight from Figure 7-23 that for scenarios S1 and S2 (when only considering the roof for implementing BIPV), the SS and SC curves are parallel between 0 to 600 kWh/m²·year, because in this range there is no change of surfaces (therefore the production remains constant too).

Moreover, the curves do not cross at any further point, since no combination of surfaces allows to achieve a better balance between SS and SC.

Figure 7-24 shows an example of the daily energy balance (21 March) for the three comparative energy-use scenarios using a heat-pump for heating and DHW.

For example, observing the graphs for scenario S3-Transformation, the daily results show that in case of scenario A-100% (0 kWh/m²·year of irradiation threshold) without taking into account any storage system, only about 10% of the PV electricity produced by the BIPV installation is used at the same time by the building (achieving between 40-50% of SS).

This means that 90% of the electricity is considered as overproduction and injected into the grid. In general, the A-100% scenario is far from being a solution adapted to the building. Moreover, an oversized installation has a number of unfavourable implications (e.g. economic, environmental).

We observe that the irradiation values leading to a better equilibrium between SS and SC are between 500 and 1'100 kWh/m²·year depending on the scenario and variant. The recommended irradiation threshold is higher when the existing oil/gas-boiler is maintained. Active surfaces on façades become important when an electric-based HVAC system (for heating and DHW) is proposed, as this system allows to use the electricity produced by the BIPV installation not only for the appliances, but also to help the production of heating and DHW.

For this archetype, the SS and SC ratio can achieve about 24-30% when sizing the installation according to the demand of the building (B-Selection), and increase to a range of 52-79% if batteries are considered (C-Batteries).

The battery sizing is dependent upon the mean daily electricity demand (as explained in Section 7.2.3), in turn affected by the HVAC system. When the HVAC system is not substituted, the electricity consumption (appliances, lighting and mechanical ventilation) does not change between the scenarios (S1, S2 and S3) and therefore the mean daily demand of electricity remains the same. However, when the HVAC system is changed, the heating and DHW demands are considered and the electricity consumption values differ between renovation scenarios, due to differences in heating demand (lower in a more performant renovation strategy). The example results from the economic study conducted to size the battery for each archetype when defining the energy-use scenario C-Batteries, showed in

Figure 7-23 (Section 7.2.3), serves to verify the consistency of the battery sizing procedure using SS and SC with a 1-day of autonomy.

Results shown in Table 7-8 define the final configurations for scenarios S1 to S3 in their different energy-use configuration (A to C) and HVAC system variant. These are used for the assessment of each group of indicators, for which results are presented below.

Active surfaces selection		**OIL/GAS**			**HP**	
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	1100	1100	0	500	500
SS [%]	41%	30%	79%	24%	24%	52%
SC [%]	19%	26%	66%	26%	27%	60%
Annual production [MWh]	31	17	17	31	29	29
BIPV surfaces [m²]	190	77	77	190	172	172
BIPV installation size [kWp] STC	33	13	13	33	29	29
Battery size [kWh]	-	-	84	-	-	172
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	1100	1100	0	600	600
SS [%]	41%	29%	79%	27%	27%	62%
SC [%]	18%	26%	66%	24%	24%	54%
Annual production [MWh]	34	17	17	34	32	32
BIPV surfaces [m²]	209	77	77	209	190	190
BIPV installation size [kWp] STC	36	13	13	36	33	33
Battery size [kWh]	-		84	-	-	144
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	1100	1100	0	800	800
SS [%]	48%	29%	79%	38%	26%	70%
SC [%]	9%	26%	66%	13%	23%	59%
Annual production [MWh]	76	17	17	76	28	28
BIPV surfaces [m²]	593	77	77	593	150	150
BIPV installation size [kWp] STC	102	13	13	102	26	26
Battery size [kWh]	-	-	84	-	-	122

Table 7-8. Values defining different BIPV scenarios and variants for Archetype 1.

Photovoltaic performance

Table 7-9 presents the results of the different indicators regarding the photovoltaic performance for each scenario of Archetype 1. These allow to verify that the proposed BIPV installation is adequate and produces energy more efficiently than the grid, both from an economic and environmental point of view.

As expected, the best values for all five indicators – i.e. highest Energy yield and lowest value for all other indicators – are obtained with the scenario B-Selection, that is, with a BIPV installation well adapted to the real needs of the building.

The lower energy yield values obtained for A-100%, especially for the S3 scenario, indicate that the size and configuration of this installation (BIPV on all façades as seen in Figure 7-23) is less efficient than those in the other scenarios.

Overall, results are much better than those obtained using the Swiss grid electricity, which presents 2.52 kWhNRE/kWhe-grid and 0.102 kgCO_2/kWhe-grid **[KBOB 2016]**. Indeed, even though the cost of a BIPV installation remains high, the LCOE, between 0.042 and 0.138 CHF/kWh, is much more beneficial than the 0.25 CHF/kWh from the grid. The same trend is obtained for the non-renewable primary energy factor and the carbon content of the PV electricity produced. In this case, values are between 0.119 and 0.316 kWhNRE/ kWhe-pv (for NREPV) and 0.031 and 0.078 kgCO_2/ kWhe-pv (for CCFPV), again better than the values from the grid which are of 2.52 and 0.102 respectively.

PV performance	OIL/GAS			HP		
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.042	0.041	0.101	0.042	0.045	0.115
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.156	0.119	0.260	0.156	0.151	0.316
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.041	0.031	0.064	0.041	0.040	0.078
$EPBT_{PV}$ [years]	3.2	2.5	5.4	3.2	3.1	6.5
$GPBT_{PV}$ [years]	11.9	9.1	18.6	11.9	11.5	22.7
Energy yield [kWh_{e-pv}/kWh_p]	957	1259		957	990	
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.056	0.068	0.122	0.056	0.076	0.120
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.157	0.119	0.260	0.157	0.152	0.277
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.041	0.031	0.064	0.041	0.040	0.069
$EPBT_{PV}$ [years]	3.3	2.5	5.4	3.3	3.1	5.7
$GPBT_{PV}$ [years]	12.0	9.1	18.6	12.0	11.5	20.0
Energy yield [kWh_{e-pv}/kWh_p]	950	1259		950	987	
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.089	0.086	0.141	0.089	0.092	0.138
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.200	0.119	0.260	0.200	0.137	0.259
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.052	0.031	0.064	0.052	0.036	0.064
$EPBT_{PV}$ [years]	4.1	2.5	5.4	4.1	2.8	5.4
$GPBT_{PV}$ [years]	15.2	9.1	18.6	15.2	10.5	18.7
Energy yield [kWh_{e-pv}/kWh_p]	748	1258		748	1090	

Table 7-9. PV performance indicator values obtained for the different BIPV scenarios and variants for Archetype 1.

In terms of energy (EPBT) and GHG emission (GPBT) payback time, all values are lower than 25 years (performance warranty period of the PV modules). The higher values are observed in the C-Batteries option and are mainly due to the environmental impact of the batteries.

These values highlight that the preconceived idea that BIPV installations are not effective in terms of environmental impact are questionable, even in the case where the active surfaces do not present an optimal orientation/inclination. In this case, the values of the energy yield, which give an idea of the production performance of the BIPV installation, are between 748 -1’258 kWhe-pv/kWhp. Logically, when the active surfaces are selected using SS and SC, a higher value of production per kWp installed is obtained.

Energy balance (operational phase)

We here present the results of the annual final energy balance for all designs and energy-use options, including energy needs and electricity produced on-site by the BIPV installation. First, it is interesting to see the effect of the passive strategies implemented for each scenario on to the power required for heating (Figure 7-25), which is reduced from 80 kW to 18 kW between E0 and S3. If the HVAC system is replaced (option HP), this reduction in the size required for the central heating system (down to 30 to 18 kW for S0-S3) automatically leads to a direct saving on the investment for the new system.

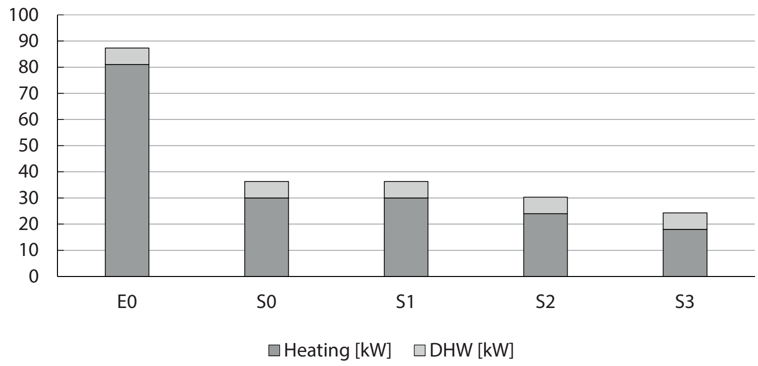
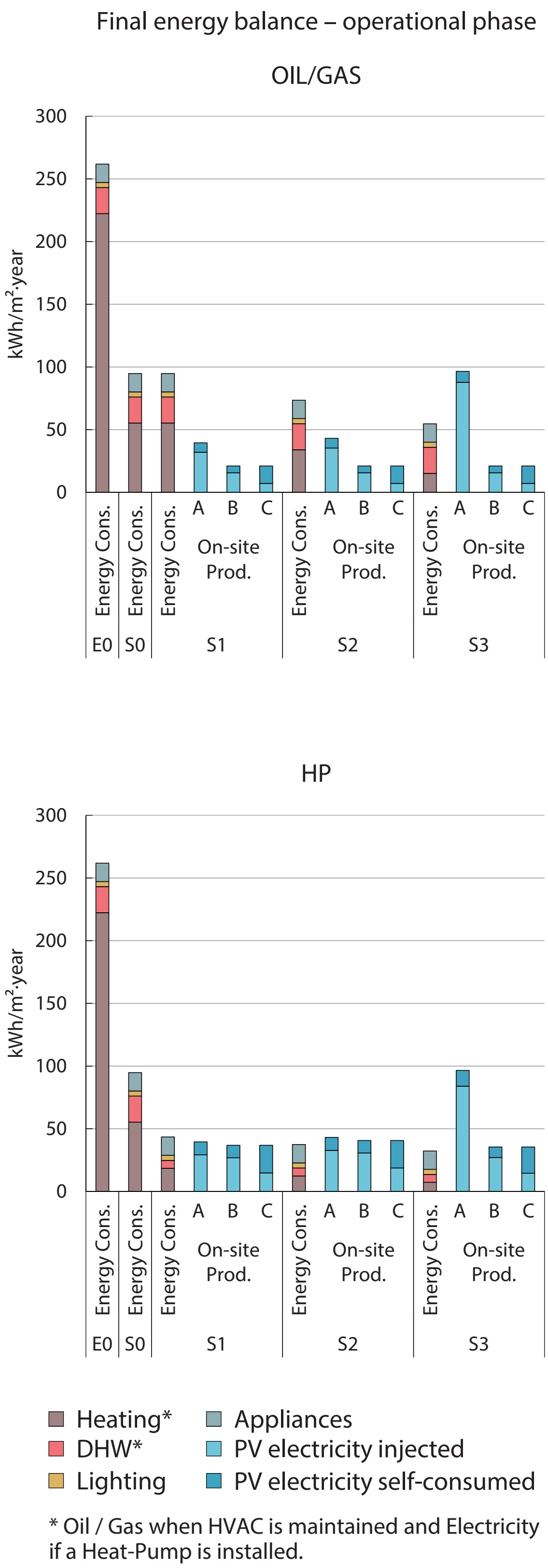


Figure 7-25. Power required for the HVAC system (heating and DHW), Archetype 1.

Observing the final energy balance presented in Figure 7-26, the considerable energy consumption of the current status (E0) highlights the importance of an energy renovation for this type of building. In scenario S0, implementing a current practice renovation without BIPV elements reduces the total energy consumption from 262 to 95 kWh/m²·year (representing a 64% of reduction). Considering only the improvement of the energy performance due to the building envelope interventions, scenarios S1 to S3 allow total savings ranging from 64% to 79% (maintaining the existing oil-boiler). If, in combination with the passive strategies, the HVAC system is replaced by a high-efficiency heat-pump, the final energy savings achieve 83% (S1), 85% (S2) and 87% (S3).

In addition, S1-S3 produce a considerable amount of electricity on-site (in blue on Figure 7-26), in some cases making the building a positive energy building that produces more energy than it needs over an annual balance.

In terms of environmental impact of the energy consumption (operational phase) considering the different energy sources (oil, gas and electricity), results for the current status (E0) are far from the 2'000-Watt Society targets for both CEDnr (target of 69.4 kWh/m²·year) and GWP (target of 5 $kgCO_2/m^2 \cdot year$). For this archetype, when the oil-boiler is not replaced and the injection is possible, only scenario (S3, A-100%) respects both limits. However, when the oil-boiler is replaced by a HP, a large number of variants comply with the targets notably for S2 and S3. Also, in case the injection is not possible, only the scenarios S1 to S3, especially with batteries, fulfil the objectives. This highlights the role that a storage system can have in these circumstances.



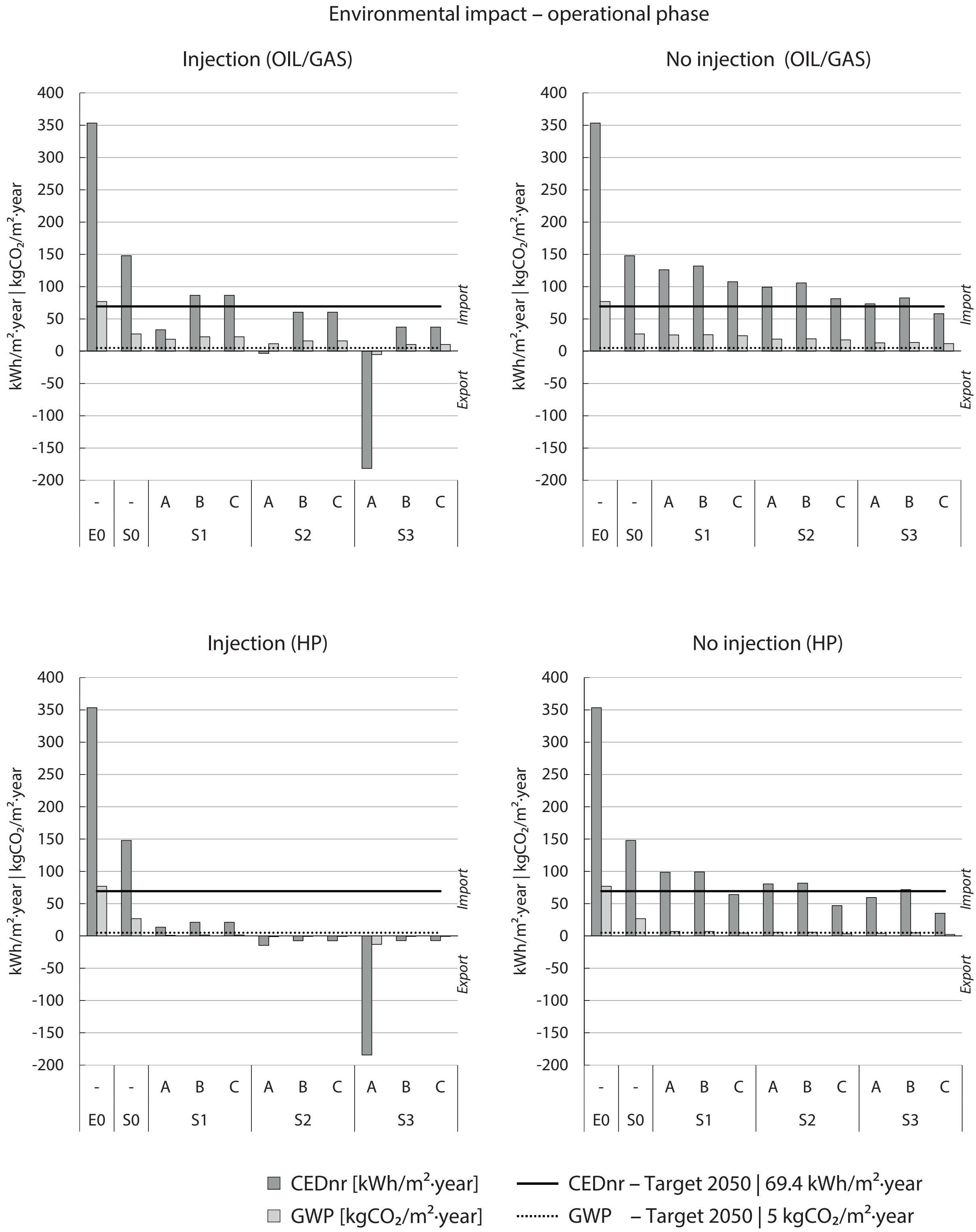


Figure 7-26. Final energy balance, non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP) for the operational phase of the Archetype 1, for each renovation scenario and energy-use scenario (A-100%, B-Selection and C-Batteries), with or without replacing the existing HVAC system and considering or not the possibility to inject into the grid.

Results for all indicators of this group are presented in Table 7-10.

Operational phase	OIL/GAS			HP		
E0 - Current Status						
Consumption [kWh/m^2·year]						
Oil		243		-		
Electricity		19				
CED_{nr} [kWh_{NRE}/m^2·year]		346				
GWP [$kgCO_2/m^2$·year]		75				
HVAC Power needed [kW]		81				
S0 - Baseline						
Consumption [kWh/m^2·year]						
Oil		76		-		
Electricity		19				
CED_{nr} [kWh_{NRE}/m^2·year]		141				
GWP [$kgCO_2/m^2$·year]		25				
HVAC Power needed [kW]		30				
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Oil		76			-	
Electricity		19			43	
PVSC [$kWh_{e\text{-}pv}/m^2$·year]	8	5	14	10	10	22
PVI [$kWh_{e\text{-}pv}/m^2$·year]	32	16	7	29	27	15
SS | SC [%]	41 | 19	30 | 26	79 | 66	24 | 26	24 | 27	52 | 60
CED_{nr} [kWh_{NRE}/m^2·year]	33	87	87	14	21	21
GWP [$kgCO_2/m^2$·year]	19	22	22	1	2	2
HVAC Power needed [kW]	30					
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Oil		55			-	
Electricity		19			37	
PVSC [$kWh_{e\text{-}pv}/m^2$·year]	8	6	14	10	10	22
PVI [$kWh_{e\text{-}pv}/m^2$·year]	35	16	7	33	31	19
SS | SC [%]	41 | 18	29 | 26	79 | 66	27 | 24	27 | 24	62 | 54
CED_{nr} [kWh_{NRE}/m^2·year]	-4	60	60	-15	-7	-7
GWP [$kgCO_2/m^2$·year]	11	16	16	-1	-1	-1
HVAC Power needed [kW]	24					
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Oil		36			-	
Electricity		19			31	
PVSC [$kWh_{e\text{-}pv}/m^2$·year]	9	6	14	13	8	21
PVI [$kWh_{e\text{-}pv}/m^2$·year]	88	16	7	84	27	15
SS | SC [%]	48 | 9	29 | 26	79 | 66	38 | 13	26 | 23	70 | 59
CED_{nr} [kWh_{NRE}/m^2·year]	-182	37	37	-184	-7	-7
GWP [$kgCO_2/m^2$·year]	-5	10	10	-13	-1	-1
HVAC Power needed [kW]	18					

Table 7-10. Final energy balance (operational phase) indicator values obtained for the different scenarios and variants for Archetype 1, taking into account the injection of the electricity overproduction into the grid. Negative values correspond to positive energy scenarios (the energy produced is higher than the consumption).

Life-Cycle Assessment (LCA)

This section shows the global LCA results, considering both the operational phase and the environmental impact of the construction materials.

Figure 7-27 and Figure 7-28 graphically show the results for all scenarios (E0, S0, S1, S2 and S3) and variants (OIL/GAS, HP, A-100%, B-Selection and C-Batteries) with the two possible approaches regarding the way in which the energy overproduced is used (with or without injection possibility). Results are expressed in CEDnr and GWP to compare with the 2'000-Watt Society targets respectively of 310 $MJ/m^2 \cdot year$ and 10 $kgCO_2/m^2 \cdot year$. In addition, Table 7-11 presents a summary of the results including the energy payback time (EPBT) and the GHG emissions payback time (GPBT).

Considering the injection of the electricity overproduced (Figure 7-27), if the oil-boiler is maintained, only the scenario S3, OIL/GAS, A-100% respects both targets. Scenario S2 respects only the CEDnr limit. However, when the oil-boiler is replaced by a HP, the three BIPV scenarios comply with the requirements of the 2'000-Watt Society.

Regarding the option when the injection into the grid is not available (Figure 7-28), the scenarios that achieve the targets are S2 and S3, but only if the oil-boiler is replaced.

It is important to highlight that the variant B-Selection allows to reach almost carbon and energy neutrality for scenarios with BIPV. In addition, comparing the graphs from Figure 7-27 and Figure 7-28, it is possible to see the role that batteries could play in achieving the 2'000-Watt Society targets, if the amount of energy to be injected into the network is limited or null (no injection possible).

An example of detailed LCA results showing the contribution of the embodied energy and carbon of the renovation, decomposed per construction element (opaque surfaces, roof, windows, BIPV, etc.) can be found in Annexe 10.7.

In terms of payback times (Table 7-11), values obtained are between 1.4-3.7 years (for EPBT) and 2-5.2 years (for GPBT) if the injection into the grid is possible, and slightly higher, between 1.6-4.4 years (for EPBT) and 2.1-5.9 years (for GPBT) without injection.

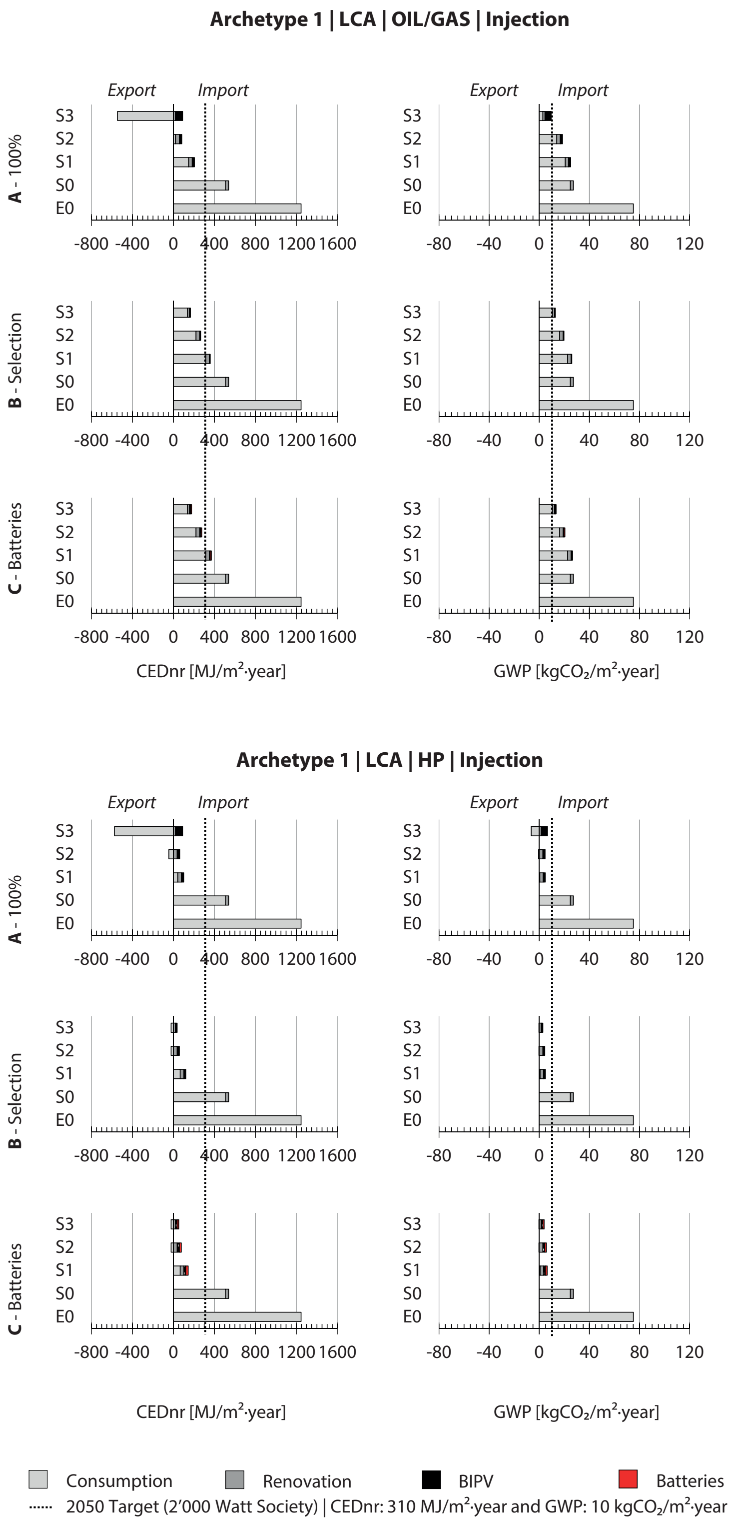


Figure 7-27. LCA results for Archetype 1 (injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

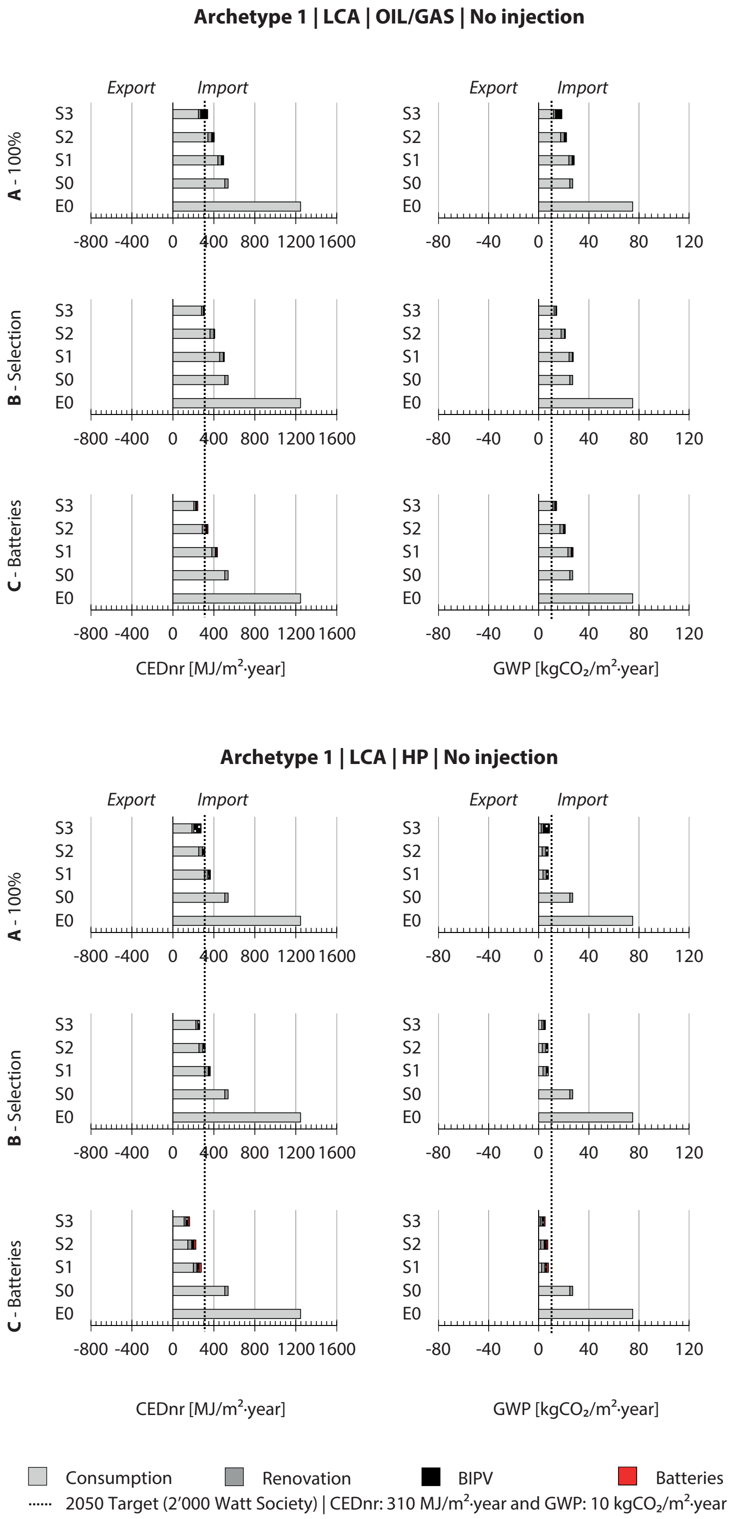


Figure 7-28. LCA results for Archetype 1 (self-consumption approach without injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

LCA	OIL/GAS			HP		
E0 – Current Status	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	1246	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	75	-	-	-	-	-
EPBT [years]	-	-	-	-	-	-
GPBT [years]	-	-	-	-	-	-
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	539	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	27	-	-	-	-	-
EPBT [years]	2.7	-	-	-	-	-
GPBT [years]	2.9	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	**200**	357	368	**95**	**118**	**139**
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	25	26	27	**5**	**5**	**6**
EPBT [years]	2.8	2.7	3.4	2.6	2.6	3.7
GPBT [years]	4.6	3.7	4.5	3.4	3.3	4.4
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	**76**	**264**	**275**	**10**	**31**	**49**
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	18	20	20	**4**	**4**	**5**
EPBT [years]	2.7	2.5	3.2	2.6	2.6	3.4
GPBT [years]	4.4	3.5	4.2	3.6	3.5	4.4
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	**-473**	**164**	**175**	**-502**	**11**	**27**
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	**9**	13	13	**0**	**3**	**4**
EPBT [years]	2.4	1.4	2.0	2.4	1.6	2.3
GPBT [years]	5.2	2.0	2.7	4.6	2.2	3.0
No Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	491	499	433	361	361	**273**
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	28	28	27	**8**	**8**	**8**
EPBT [years]	3.9	3.2	3.6	3.4	3.3	4.2
GPBT [years]	4.9	3.9	4.6	3.5	3.4	4.5
S2 – BIPV Renovation	**A**	**B**	**C**	A	B	C
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	397	406	340	**308**	**310**	**219**
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	22	21	21	**7**	**7**	**7**
EPBT [years]	3.7	2.9	3.4	3.4	3.3	4.0
GPBT [years]	4.7	3.6	4.3	3.8	3.6	4.5
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	323	**306**	**240**	**259**	**258**	**159**
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	18	14	14	**8**	**5**	**5**
EPBT [years]	4.4	1.6	2.1	4.2	2.0	2.6
GPBT [years]	5.9	2.1	2.7	5.1	2.3	3.1

Table 7-11. LCA indicator values obtained for the different scenarios and variants for Archetype 1, with and without injection possibility. Values in bold respect the 2050 targets (2’000-Watt Society).

Life-cycle cost (LCC)

This section shows the results of the life-cycle cost assessment to give an overview of the cost-effectiveness of the different renovation scenarios. First, we present in Figure 7-29 the cumulative energy consumption cost during a horizon of 50 years. Each curve corresponds to a scenario (E0-S3), and begins with a value equivalent to the initial investment (detailed information in Annexe 10.5). The only curve that starts at zero is the current status (E0) of the building.

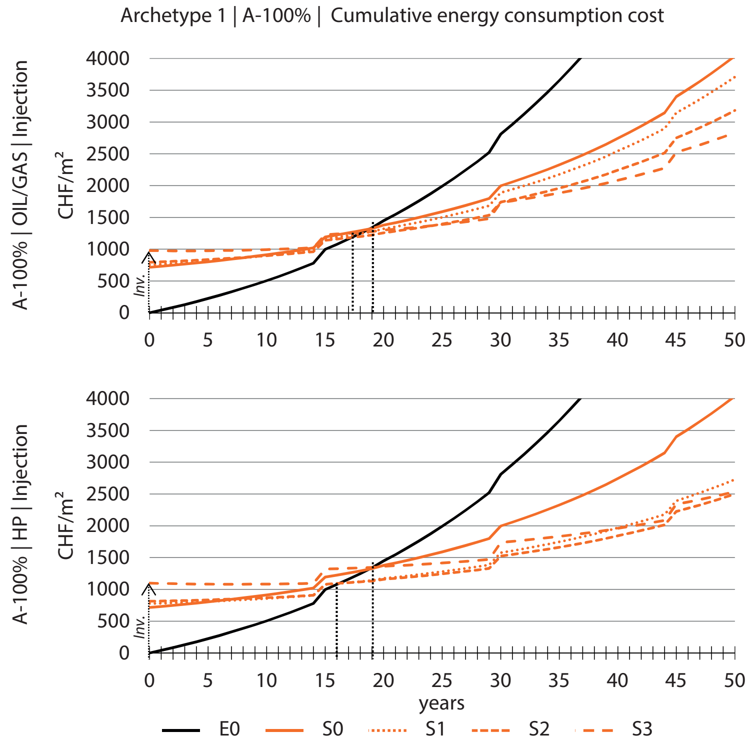


Figure 7-29. Cumulative energy consumption cost for Archetype 1, considering A-100%, OIL/GAS, HP and Injection.

Irregularities in the curves correspond to future investments made on maintenance or renovation of damaged parts reaching their end of life (e.g. facilities, windows). These investment values are estimated to be of about 15-20% of the initial investment of the corresponding renovation project.

The year at which the orange curves (scenarios S0 to S3) cross the E0 curve represents the simple payback time (SPBT), calculated without considering actualisation of prices. As mentioned in Section 7.2.2, the calculation takes into account a cost increase of the energy (2.5%/year), 0.8%/year of PV production degradation, a decrease of FiT of 5%/year and major maintenance works every 15 years.

This graphical representation allows us to rapidly capture the advantage of the BIPV renovation scenarios. Especially when the oil-boiler is replaced, the SPBT of BIPV scenarios are lower compared to a current practice renovation (S0); between S0 and S1 for instance, the SPBT goes from 18 to 16 years. Considering that the renovation works conducted are almost the same, with the main difference being the BIPV installation, these results allow to see how the integration of BIPV strategies could help to improve the cost-effectiveness of the whole renovation project, but also the importance of complementing the building envelope improvement with the replacement of existing HVAC systems based on fossil fuels. In addition to a shorter payback time, the energy savings along the life-cycle are not negligible.

Applying a discounted-cash flow approach as introduced in Section 7.2.2, calculations are conducted for a 30-year horizon in order to compare the profitability of the investment with an alternative investment offering 3% of interest rate. The assumption here is to use the total energy savings as income cash-flow to recover the initial investment, not considering the fact that in rental buildings, the cost of energy is fully assumed by the tenants, and the owner, who invests, does not benefit from these savings. However, as previously mentioned, solutions of contracting with ESCO companies could help to overcome this barrier. Here, we aim to show the theoretical profitability due to the improvement of the global performance of the building.

Figure 7-30 presents the results for all scenarios and variants (blue dot when injection is possible and red cross when not). For current practice renovation (S0), the internal rate of return representing the annual profitability of the investment achieves 4.7%. This value is quite high compared to the expectations of an investor, mainly due to the very low performance of the current status (E0) situation. Observing the results for the BIPV scenarios, in general, for the S1 and S2 scenarios the IRR is higher. However, for S3, it is similar or lower than for S0. This situation is due to the size of the building and that the use of the most exposed surfaces of the roof and the main façade is enough to achieve good performances.

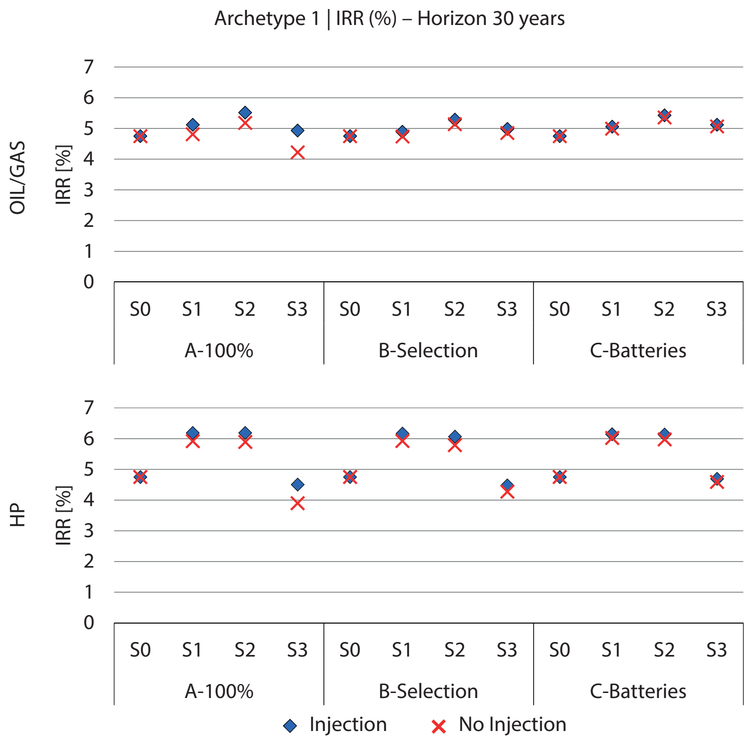


Figure 7-30. Internal rate of return (IRR) for Archetype 1 with a 30-year horizon of each renovation scenario, taking into account the different energy-use scenarios (A, B, and C).

It is interesting to highlight that the profitability of the energy-use scenario A-100% highly depends on the possibility to inject the overproduction into the grid. In addition, when the oil-boiler is replaced, the IRR increases by about 1% for S1 and S2.

Results for all economic indicators are presented in Table 7-12, including the global investment cost (fully detailed in in Annexe 10.5), the net-present value (NPV) of the investment after 30 years, the IRR, the discounted-payback time (DPB) corresponding to the year when the NPV becomes positive or the IRR is equal to the discounted rate (3%), and finally the SPBT.

LCC	OIL/GAS			HP		
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m2]	715	-	-	-	-	-
NPV* [CHF/m2]	222	-	-	-	-	-
IRR* [%]	4.7	-	-	-	-	-
DPBT [years]	24	-	-	-	-	-
SPBT [years]	18	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	753	748	775	777	776	831
NPV* [CHF/m2]	282	250	286	461	458	489
IRR* [%]	5.1	4.9	5.1	6.2	6.2	6.1
DPBT [years]	23	24	23	20	20	20
SPBT [years]	17	18	18	16	16	16
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	795	787	813	814	822	867
NPV* [CHF/m2]	359	323	359	481	465	506
IRR* [%]	5.5	5.3	5.4	6.2	6.1	6.1
DPBT [years]	22	22	22	20	20	20
SPBT [years]	17	17	17	16	16	16
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	977	887	913	1098	1022	1061
NPV* [CHF/m2]	317	311	346	272	257	311
IRR* [%]	4.9	5.0	5.1	4.5	4.5	4.7
DPBT [years]	23	23	23	24	25	24
SPBT [years]	18	18	18	19	19	19
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	753	748	775	777	776	831
NPV* [CHF/m2]	242	230	277	425	424	471
IRR* [%]	4.8	4.7	5.0	5.9	5.9	6.0
DPBT [years]	24	24	23	21	21	21
SPBT [years]	18	18	18	16	16	16
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	795	787	813	814	822	867
NPV* [CHF/m2]	313	303	349	439	425	482
IRR* [%]	5.2	5.1	5.4	5.9	5.8	6.0
DPBT [years]	23	23	22	21	21	21
SPBT [years]	18	18	17	16	17	16
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	977	887	913	1098	1022	1061
NPV* [CHF/m2]	203	290	337	163	222	292
IRR* [%]	4.2	4.9	5.1	3.9	4.3	4.6
DPBT [years]	25	24	23	26	25	24
SPBT [years]	19	18	18	20	19	19

Table 7-12. LCC indicator values obtained for the different scenarios and variants for Archetype 1, with and without injection possibility. * Horizon of 30 years for NPV and IRR calculations.

Indoor comfort

Figure 7-31 shows the number of hours at more than 26.5°C over the year and the results of the daylighting study in terms of Daylight Autonomy (map), spatial Daylight Autonomy (% floor area), and Daylight Factor (%) for a representative floor. These results serve to verify that the scenarios with high insulation respect the overheating limit (of 100 hours/year with indoor temperature above 26.5°C), and that the impact on daylighting of the insulation and modification of the window sizes compared to the current status (E0) is limited (slight decrease of the sDA from 89% to 85% from E0 to S3).

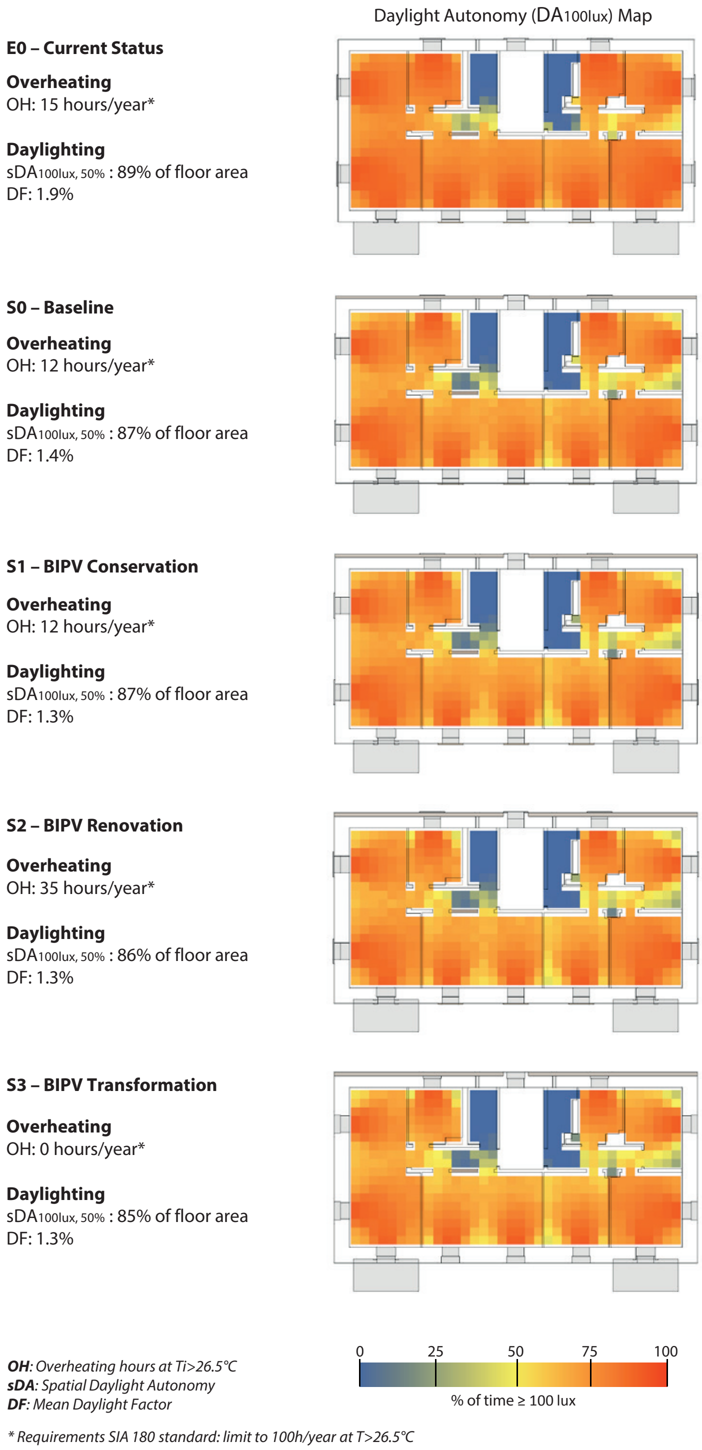
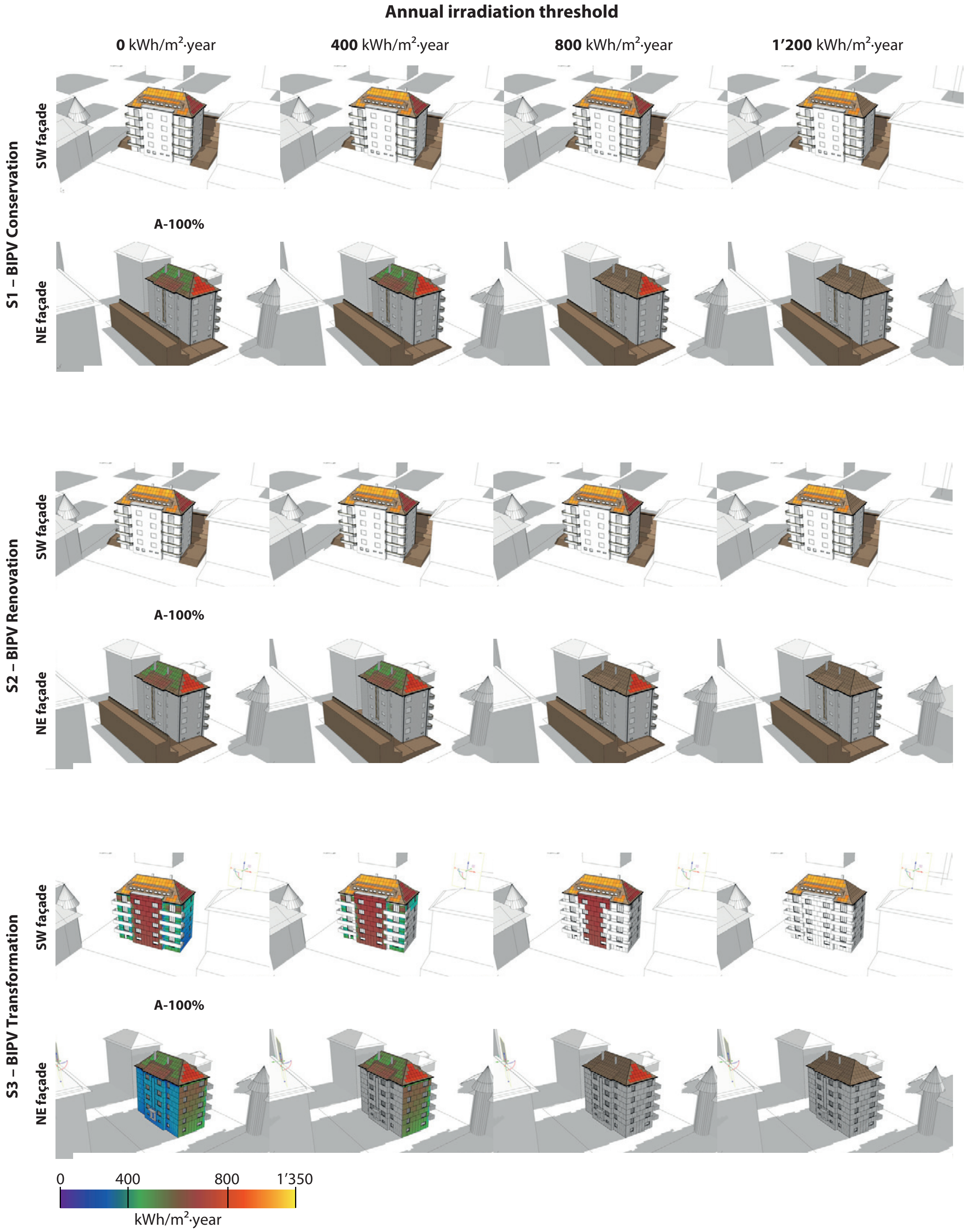


Figure 7-31. Results of the overheating and daylighting study for Archetype 1.

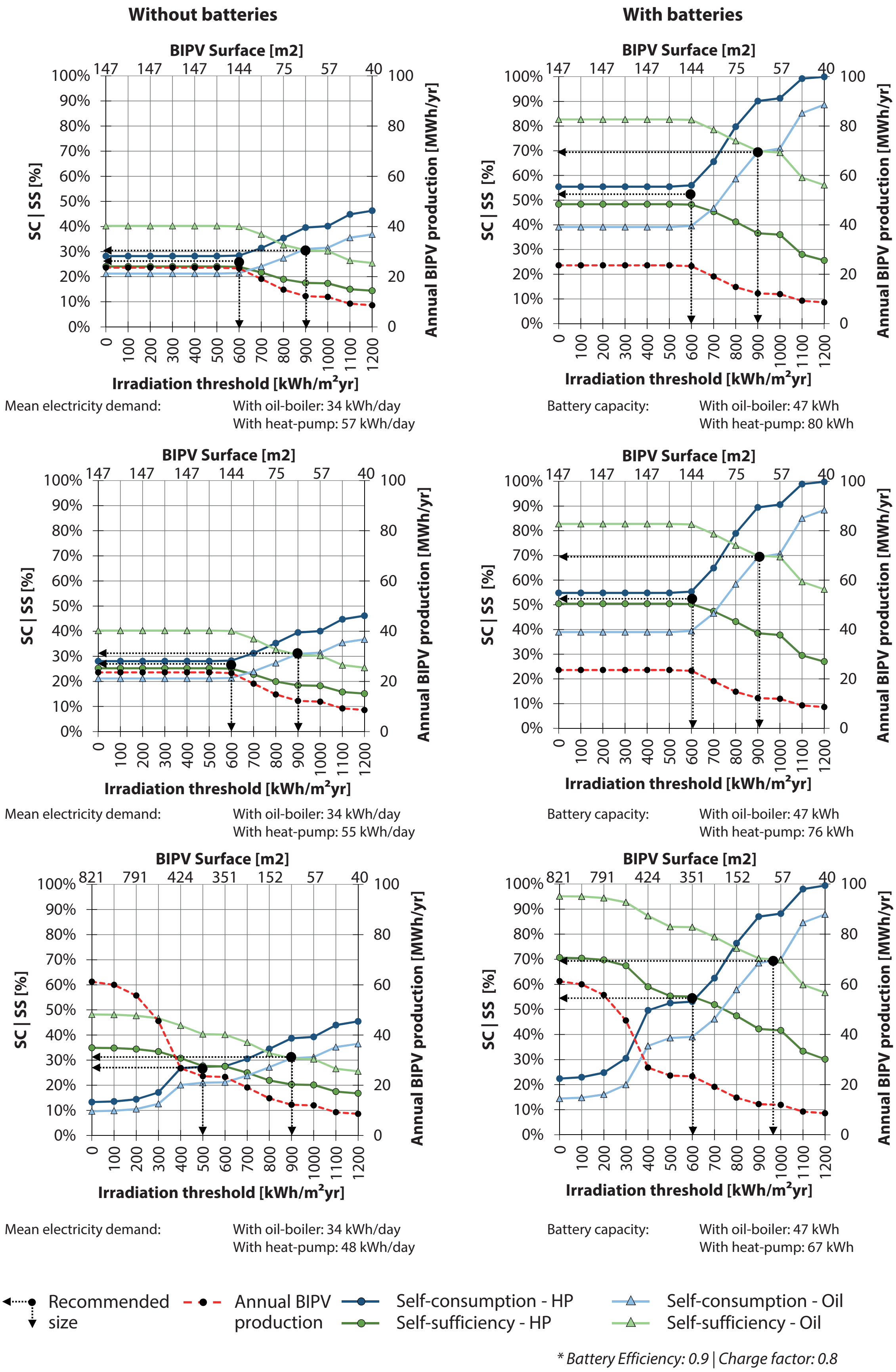
7.3.2. Archetype 2

Sizing of BIPV installation

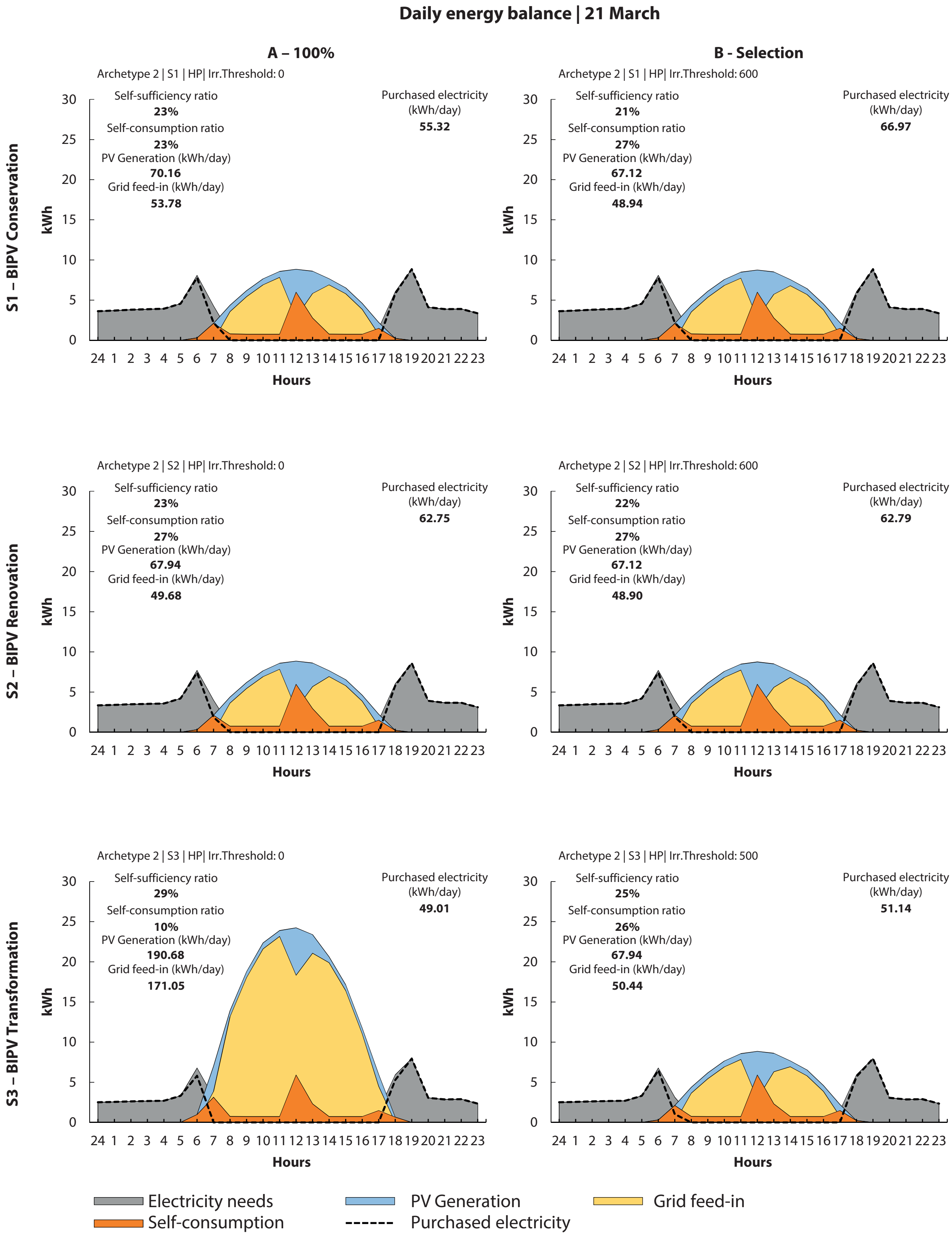
Figure 7-32 presents the results of the active surfaces selection for Archetype 2. For this archetype, mainly due to the similar shape and façade orientation, values follow the same trend than the Archetype 1. However, in this case, when the existing gas-boiler is maintained, the better equilibrium between SS and SC is achieved at 900 $kWh/m^2 \cdot year$.



Annual irradiation threshold
0 kWh/m²·year
400 kWh/m²·year
800 kWh/m²·year
1’200 kWh/m²·year
S1 – BIPV Conservation
SW façade
NE façade
A-100%
S2 – BIPV Renovation
SW façade
NE façade
A-100%
S3 – BIPV Transformation
SW façade
NE façade
A-100%
0
400
800
1’350
kWh/m²·year

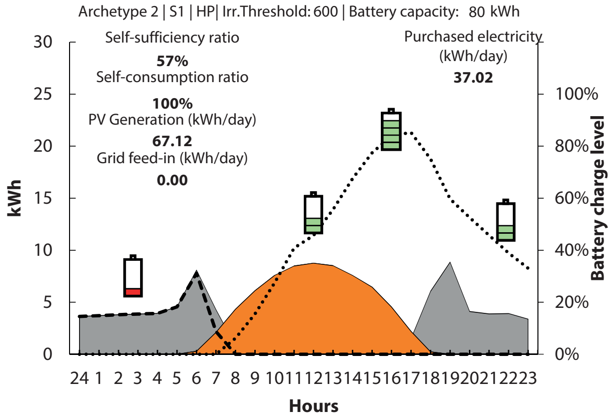


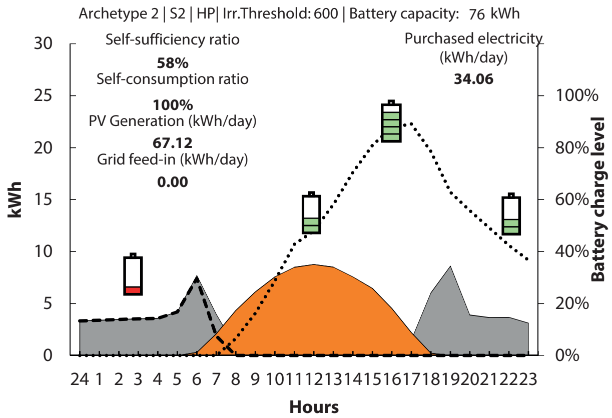
Without batteries
With batteries
BIPV Surface [m2]
SC | SS [%]
Annual BIPV production [MWh/yr]
Irradiation threshold [kWh/m²yr]
Mean electricity demand: With oil-boiler: 34 kWh/day With heat-pump: 57 kWh/day
Battery capacity: With oil-boiler: 47 kWh With heat-pump: 80 kWh
Mean electricity demand: With oil-boiler: 34 kWh/day With heat-pump: 55 kWh/day
Battery capacity: With oil-boiler: 47 kWh With heat-pump: 76 kWh
Mean electricity demand: With oil-boiler: 34 kWh/day With heat-pump: 48 kWh/day
Battery capacity: With oil-boiler: 47 kWh With heat-pump: 67 kWh
Recommended size
Annual BIPV production
Self-consumption - HP
Self-sufficiency - HP
Self-consumption - Oil
Self-sufficiency - Oil
* Battery Efficiency: 0.9 | Charge factor: 0.8

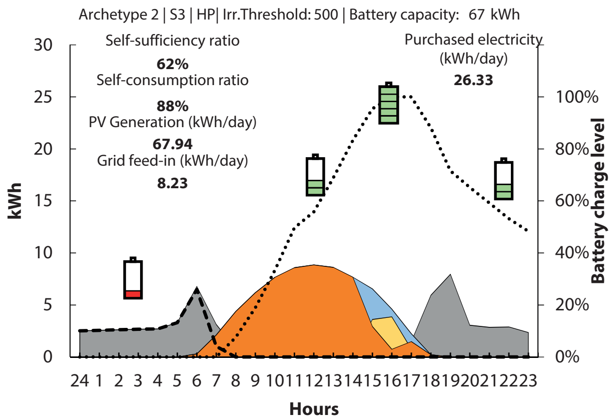


Daily energy balance | 21 March
A – 100%
B - Selection
S1 – BIPV Conservation
Archetype 2 | S1 | HP| Irr.Threshold: 0
Self-sufficiency ratio 23%
Self-consumption ratio 23%
PV Generation (kWh/day) 70.16
Grid feed-in (kWh/day) 53.78
Purchased electricity (kWh/day) 55.32
Archetype 2 | S1 | HP| Irr.Threshold: 600
Self-sufficiency ratio 21%
Self-consumption ratio 27%
PV Generation (kWh/day) 67.12
Grid feed-in (kWh/day) 48.94
Purchased electricity (kWh/day) 66.97
S2 – BIPV Renovation
Archetype 2 | S2 | HP| Irr.Threshold: 0
Self-sufficiency ratio 23%
Self-consumption ratio 27%
PV Generation (kWh/day) 67.94
Grid feed-in (kWh/day) 49.68
Purchased electricity (kWh/day) 62.75
Archetype 2 | S2 | HP| Irr.Threshold: 600
Self-sufficiency ratio 22%
Self-consumption ratio 27%
PV Generation (kWh/day) 67.12
Grid feed-in (kWh/day) 48.90
Purchased electricity (kWh/day) 62.79
S3 – BIPV Transformation
Archetype 2 | S3 | HP| Irr.Threshold: 0
Self-sufficiency ratio 29%
Self-consumption ratio 10%
PV Generation (kWh/day) 190.68
Grid feed-in (kWh/day) 171.05
Purchased electricity (kWh/day) 49.01
Archetype 2 | S3 | HP| Irr.Threshold: 500
Self-sufficiency ratio 25%
Self-consumption ratio 26%
PV Generation (kWh/day) 67.94
Grid feed-in (kWh/day) 50.44
Purchased electricity (kWh/day) 51.14
kWh
Hours
Electricity needs
PV Generation
Grid feed-in
Self-consumption
Purchased electricity

C - Batteries







The main difference is that, for this building, the part of the roof facing east and west is larger than in Archetype 1. This irradiation value of 900 kWh/m²·year indicates the importance of considering these surfaces for the integration of active elements as they help to improve the match between PV production and the building electricity demand. If the gas-boiler is replaced by a heat-pump, the surfaces with at least 500-600 kWh/m²·year should be considered, highlighting the importance of taking into account façade surfaces.

Similarly to Archetype 1, the SS-SC curves are parallel between 0 to 600 kWh/m²·year and do not cross at any precise point.

Figure 7-33 shows an example of the daily energy balance (21 March) for the Archetype 2. The results are close to the previous archetype, showing a SS between 21-62% and a SC ranging from 10% to 100% (for the scenarios with batteries).

Table 7-13 presents the values defining the final configurations for scenarios S1 to S3 in their different energy-use configuration (A to C) and HVAC system variant for Archetype 2. We observe that the irradiation values leading to a better equilibrium between SS and SC are between 500 and 900 kWh/m²·year depending on the scenario and variant.

For this archetype, when sizing the installation according to the demand of the building (B-Selection), the SS and SC ratio can achieve about 31% (maintaining the gas-boiler) and 24-28% (implementing a HP), and increase to a range of 48-70% if batteries are considered (C-Batteries).

Active surfaces selection		**OIL/GAS**			**HP**	
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	900	900	0	500	500
SS [%]	40%	31%	70%	24%	24%	48%
SC [%]	21%	31%	69%	28%	28%	55%
Annual production [MWh]	24	12	12	24	24	24
BIPV surfaces [m²]	147	59	59	147	147	147
BIPV installation size [kWp] STC	25	10	10	25	25	24
Battery size [kWh]	-	-	71	-	-	120
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	900	900	0	500	500
SS [%]	41%	31%	70%	25%	25%	50%
SC [%]	21%	31%	69%	28%	28%	55%
Annual production [MWh]	27	12	12	27	24	24
BIPV surfaces [m²]	147	59	59	147	147	147
BIPV installation size [kWp] STC	25	10	10	25	25	25
Battery size [kWh]	-		71	-	-	114
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	900	900	0	500	500
SS [%]	48%	31%	70%	35%	28%	55%
SC [%]	10%	31%	69%	13%	27%	53%
Annual production [MWh]	62	12	12	62	27	27
BIPV surfaces [m²]	821	58	58	821	375	375
BIPV installation size [kWp] STC	141	10	10	141	64	64
Battery size [kWh]	-	-	71	-	-	100

Table 7-13. Values defining different BIPV scenarios and variants for Archetype 2.

Photovoltaic performance

Table 7-14 presents the results of the different indicators regarding the photovoltaic performance for each scenario of Archetype 2.

In general, this case study presents worst values than those obtained for Archetype 1, mainly due to the closer context with more solar obstructions. The lower Energy yield values are obtained for scenario S3, especially for A-100% OIL/GAS (440 kWhe-pv/kWhp) and B-Selection and C-Batteries HP (424 kWhe-pv/kWhp). These results indicate that the size and configuration of this installation (BIPV on all façades as seen in Figure 7-32) is less efficient than those in the other scenarios, and the addition of batteries does not help to improve the situation.

In terms of carbon content of the electricity produced by the BIPV installation, results are better than those obtained using the Swiss grid electricity, with the exception of scenario (S3, C-Batteries), which has a value of 0.133 $kgCO_2$/kWhe-pv, higher than the 0.102 $kgCO_2$/kWhe-grid of the grid. For all cases with batteries (as well as for the S3 A-100% scenarios), results are not good enough to ensure the recovery of emissions produced in the manufacture of the photovoltaic installation before 25 years. In conclusion, batteries have an environmental impact too high that the configuration of the BIPV elements cannot compensate.

PV performance	OIL/GAS			HP		
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/$kWh_{e\text{-}pv}$]	0.044	0.049	0.128	0.044	0.050	0.118
NRE_{PV} [kWh_{NRE}/ $kWh_{e\text{-}pv}$]	0.160	0.124	0.402	0.160	0.159	0.403
CCF_{PV} [$kgCO_2$/ $kWh_{e\text{-}pv}$]	0.042	0.032	0.097	0.042	0.042	0.098
$EPBT_{PV}$ [years]	3.3	2.6	8.3	3.3	3.3	8.3
$GPBT_{PV}$ [years]	12.2	9.4	28.3	12.2	12.1	28.6
Energy yield [$kWh_{e\text{-}pv}$/kWh_p]	937	1207		937	939	
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/$kWh_{e\text{-}pv}$]	0.039	0.049	0.128	0.039	0.050	0.115
NRE_{PV} [kWh_{NRE}/ $kWh_{e\text{-}pv}$]	0.142	0.124	0.402	0.142	0.159	0.391
CCF_{PV} [$kgCO_2$/ $kWh_{e\text{-}pv}$]	0.037	0.032	0.097	0.037	0.042	0.095
$EPBT_{PV}$ [years]	2.9	2.6	8.3	2.9	3.3	8.1
$GPBT_{PV}$ [years]	10.8	9.4	28.3	10.8	12.1	27.8
Energy yield [$kWh_{e\text{-}pv}$/kWh_p]	1057	1207		1057	939	
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/$kWh_{e\text{-}pv}$]	0.157	0.102	0.168	0.157	0.237	0.235
NRE_{PV} [kWh_{NRE}/ $kWh_{e\text{-}pv}$]	0.340	0.125	0.402	0.340	0.353	0.528
CCF_{PV} [$kgCO_2$/ $kWh_{e\text{-}pv}$]	0.089	0.033	0.097	0.089	0.092	0.133
$EPBT_{PV}$ [years]	7.0	2.6	8.3	7.0	7.3	10.9
$GPBT_{PV}$ [years]	25.9	9.5	28.3	25.9	26.8	38.7
Energy yield [$kWh_{e\text{-}pv}$/kWh_p]	440	1195		440	424	

Table 7-14. PV performance indicator values obtained for the different BIPV scenarios and variants for Archetype 2.

Energy balance (operational phase)

We here present the results of the annual final energy balance for Archetype 2, starting with the resulting power required for heating (Figure 7-34), which is reduced progressively according to the intensity of the intervention from 95 kW (for E0) to 32, 28, 25 and 21 kW for S0, S1, S2 and S3 respectively.

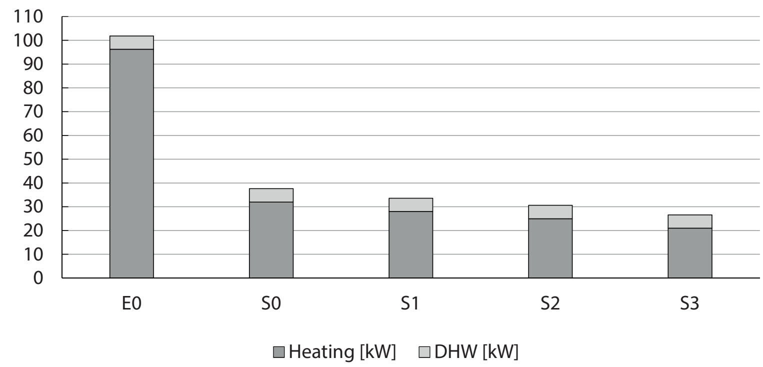
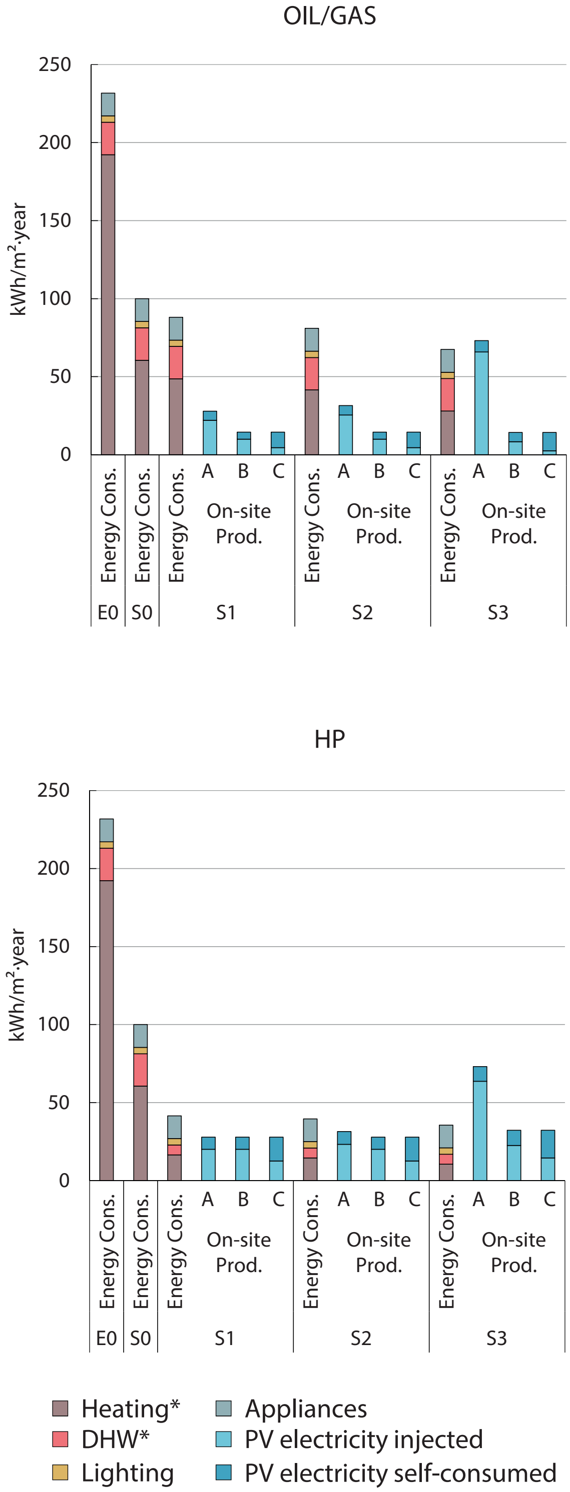


Figure 7-34. Power required for the HVAC system (heating and DHW), Archetype 2.

Observing the final energy balance presented in Figure 7-35, the energy savings reach 56% only with passive strategies complying with minimum legal requirement (S0). For the other scenarios, considering only the improvement of the energy performance due to the building envelope interventions, total savings range from 62% to 71% (maintaining the gas-boiler). If in combination with the passive strategies the HVAC system is replaced, the final energy saving exceeds 80% for S1, S2, and S3. In addition, considering the amount of electricity produced on-site (in blue on Figure 7-35), scenario S3 A-100% becomes a positive energy building.

In terms of environmental impact of the energy consumption (operational phase), only scenarios for which the gas-boiler is replaced by a heat-pump, along with scenario S3, A-100% achieve both CEDnr (69.4 kWh/m²·year) and GWP (5 $kgCO_2$/m²·year) 2'000-Watt Society targets. Scenarios S3 B-Selection and S3 C-Batteries are able to achieve only the CEDnr target. When injection is not possible, only the scenario S3 with batteries fulfils the objectives, highlighting the possible role that could have of a storage system.

Final energy balance – operational phase



* Oil / Gas when HVAC is maintained and Electricity if a Heat-Pump is installed.

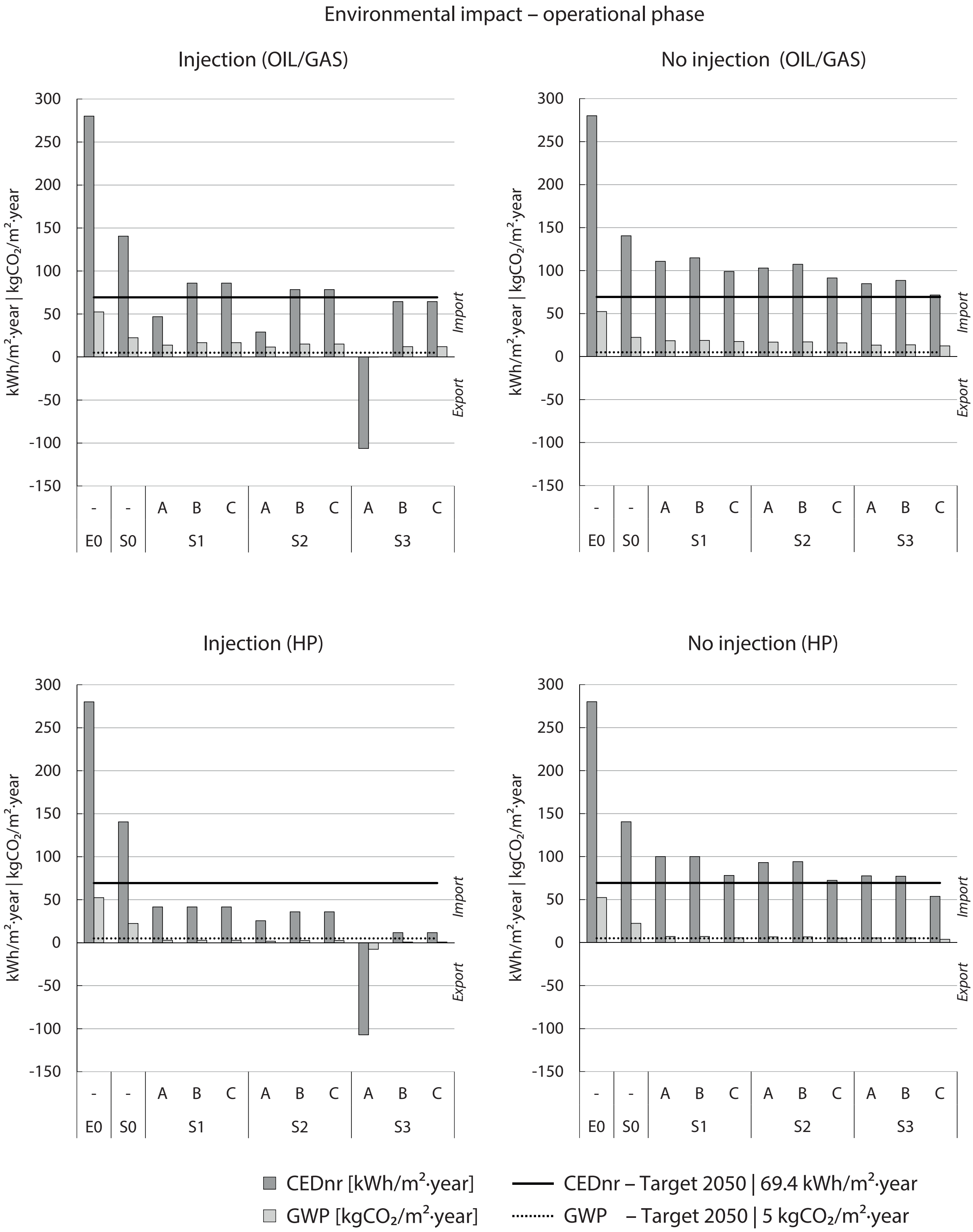


Figure 7-35. Final energy balance, non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP) for the operational phase of the Archetype 2, for each renovation scenario and energy-use scenario (A-100%, B-Selection and C-Batteries), with or without replacing the existing HVAC system and considering or not the possibility to inject into the grid.

Results for all indicators of this group are presented in Table 7-15.

Operational phase	OIL/GAS			HP		
E0 - Current Status						
Consumption [kWh/m²·year]						
Gas		213			-	
Electricity		19				
CED_{nr} [kWh_{NRE}/m²·year]		273				
GWP [$kgCO_2$/m²·year]		50				
HVAC Power needed [kW]		96				
S0 - Baseline						
Consumption [kWh/m²·year]						
Gas		81			-	
Electricity		19				
CED_{nr} [kWh_{NRE}/m²·year]		133				
GWP [$kgCO_2$/m²·year]		20				
HVAC Power needed [kW]		32				
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m²·year]						
Gas		69			-	
Electricity		19			41	
PVSC [kWh_{e-pv}/m²·year]	6	4	10	8	8	15
PVI [kWh_{e-pv}/m²·year]	22	10	4	20	20	13
SS | SC [%]	40 | 21	31 | 31	70 | 69	24 | 28	24 | 28	48 | 55
CED_{nr} [kWh_{NRE}/m²·year]	47	86	86	42	42	42
GWP [$kgCO_2$/m²·year]	14	17	17	3	3	3
HVAC Power needed [kW]			28			
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m²·year]						
Gas		62			-	
Electricity		19			40	
PVSC [kWh_{e-pv}/m²·year]	6	4	10	8	8	15
PVI [kWh_{e-pv}/m²·year]	25	10	4	23	20	13
SS | SC [%]	41 | 19	31 | 31	70 | 69	26 | 26	25 | 28	50 | 55
CED_{nr} [kWh_{NRE}/m²·year]	29	78	78	26	36	36
GWP [$kgCO_2$/m²·year]	12	15	15	2	3	3
HVAC Power needed [kW]			25			
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m²·year]						
Gas		49			-	
Electricity		19			36	
PVSC [kWh_{e-pv}/m²·year]	7	6	12	10	10	18
PVI [kWh_{e-pv}/m²·year]	66	8	2	64	23	14
SS | SC [%]	48 | 10	34 | 42	62 | 83	35 | 13	30 | 03	57 | 55
CED_{nr} [kWh_{NRE}/m²·year]	-106	65	65	-107	12	12
GWP [$kgCO_2$/m²·year]	0	12	12	-8	1	1
HVAC Power needed [kW]			21			

Table 7-15. Final energy balance (operational phase) indicator values obtained for the different scenarios and variants for Archetype 2, taking into account the injection of the electricity overproduction into the grid. Negative values correspond to positive energy scenarios (the energy produced is higher than the consumption).

Life-Cycle Assessment (LCA)

This section shows the global LCA results for Archetype 2, considering both the operational phase and the environmental impact of the construction materials. Figure 7-36 and Figure 7-37 graphically show the results for all scenarios and variants including with or without injection possibility. In addition, Table 7-16 presents a summary of the results including the energy payback time (EPBT) and the GHG emissions payback time (GPBT).

Considering the injection of the electricity overproduced (Figure 7-36), if the gas-boiler is maintained, none of the scenarios respect both limits (CEDnr and GWP). However, when the gas-boiler is replaced by a HP, the three BIPV scenarios comply with the requirements of the 2'000-Watt Society (310 MJ/m^2·year and 10 kgCO_2/m^2·year). If the injection into the grid is not available (Figure 7-37), only options B-Selection and C-Batteries when the gas-boiler is replaced achieve both targets.

In terms of payback times (Table 7-16), values obtained are between 2.5-5 years (for EPBT) and 3.7-10.6 years (for GPBT) if the injection into the grid is possible, and slightly higher, between 2.8-8.3 years (for EPBT) and 3.8-12.5 years (for GPBT) without injection.

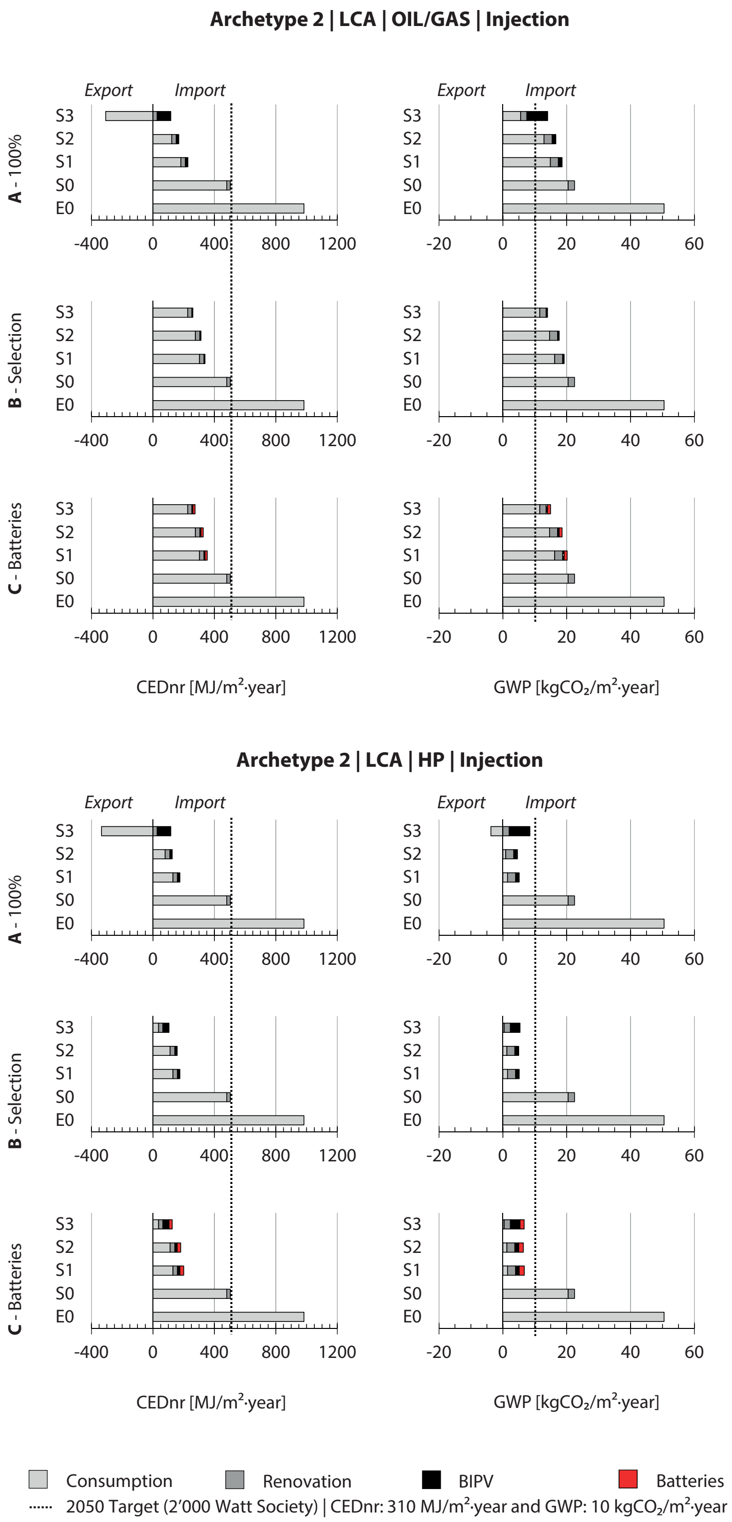


Figure 7-36. LCA results for Archetype 2 (injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

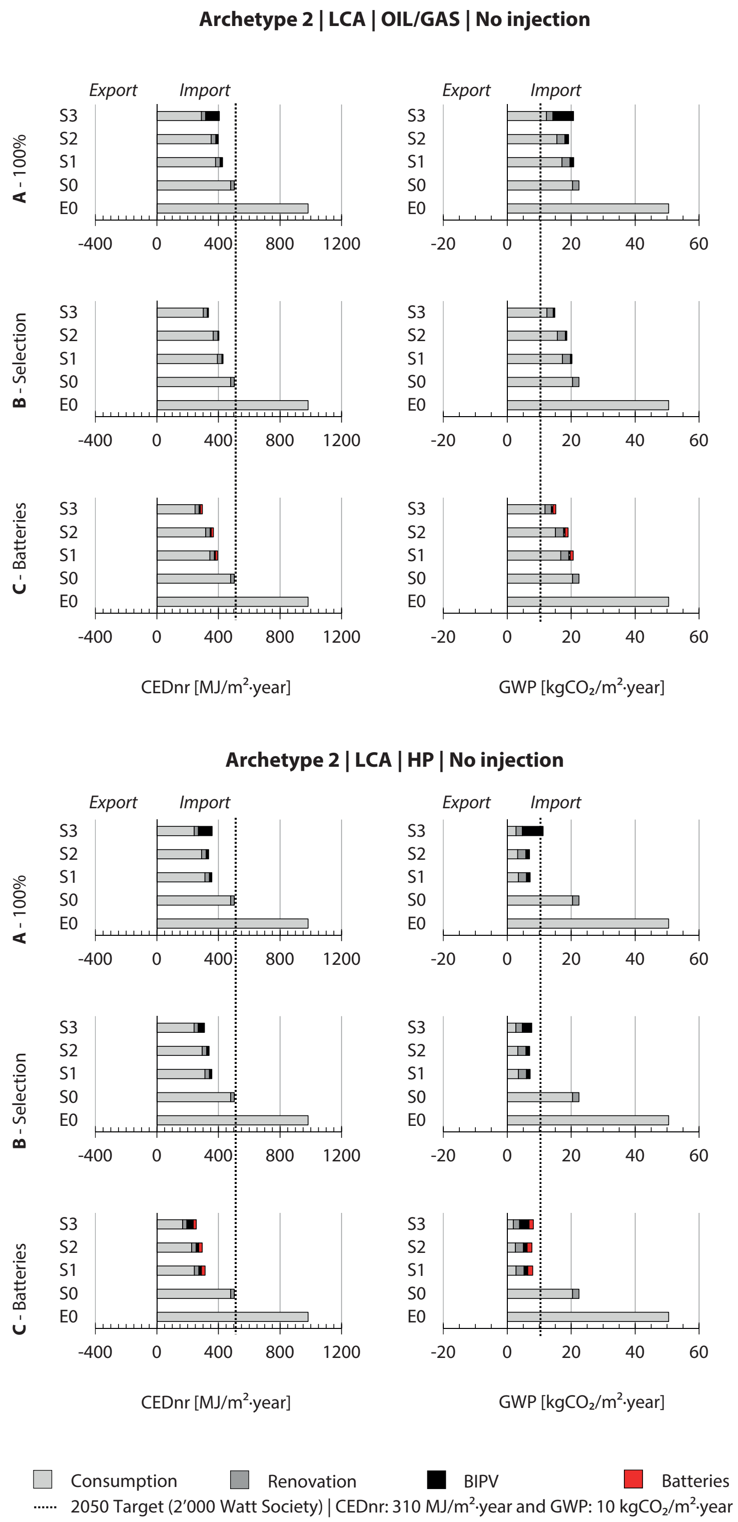


Figure 7-37. LCA results for Archetype 2 (self-consumption approach without injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

LCA	OIL/GAS			HP		
E0 – Current Status	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	983	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	50	-	-	-	-	-
EPBT [years]	-	-	-	-	-	-
GPBT [years]	-	-	-	-	-	-
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	503	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	22	-	-	-	-	-
EPBT [years]	2.7	-	-	-	-	-
GPBT [years]	4.0	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	223	338	352	173	172	197
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	18	19	20	5	5	7
EPBT [years]	3.1	3.0	4.3	3.0	3.0	4.7
GPBT [years]	6.0	5.1	6.8	4.4	4.4	6.4
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	164	311	325	122	155	178
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	16	18	19	5	5	6
EPBT [years]	2.9	2.9	4.2	2.8	2.9	4.5
GPBT [years]	5.7	4.9	6.5	4.4	4.4	6.3
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	-212	258	272	-238	96	116
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	14	14	15	4	5	6
EPBT [years]	4.5	2.5	3.7	4.4	3.8	5.0
GPBT [years]	10.6	3.7	5.1	8.8	5.7	7.3
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	423	428	393	354	354	311
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	21	20	21	7	7	8
EPBT [years]	4.1	3.5	4.6	3.8	3.8	5.4
GPBT [years]	6.4	5.3	6.9	4.6	4.6	6.5
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	395	401	366	333	337	292
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	19	19	19	7	7	8
EPBT [years]	4.0	3.4	4.4	3.7	3.7	5.2
GPBT [years]	6.2	5.1	6.6	4.6	4.6	6.4
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	385	333	294	339	300	248
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	20	15	15	11	7	8
EPBT [years]	8.3	2.8	3.8	7.8	4.8	5.9
GPBT [years]	12.5	3.8	5.2	10.0	6.0	7.5

Table 7-16. LCA indicator values obtained for the different scenarios and variants for Archetype 2, with and without injection possibility. Values in bold respect the 2050 targets (2'000-Watt Society).

Life-cycle cost (LCC)

This section shows the results of the life-cycle cost assessment for Archetype 2 to give an overview of the cost-effectiveness of the different renovation scenarios. Figure 7-38 presents the cumulative energy consumption cost during a horizon of 50 years. The starting point of each orange curve corresponds to the initial investment (detailed information in Annexe 10.5). The SPBT of BIPV scenarios are generally lower compared to S0; between S0 and S1 for instance, the SPBT goes from 24 to 22 years (gas-boiler), mainly due to the effect of implementing a BIPV strategy.

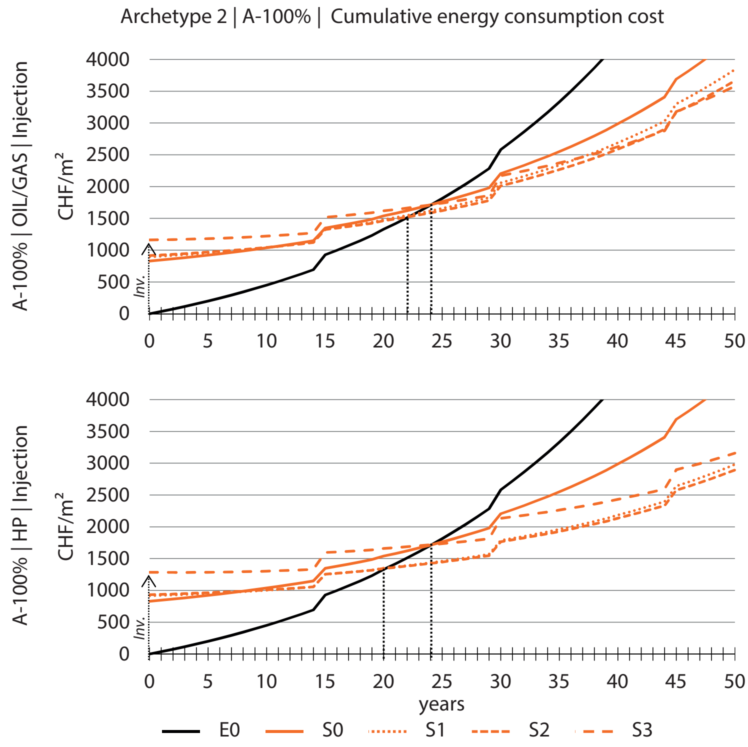


Figure 7-38. Cumulative energy consumption cost for Archetype 2, considering A-100%, OIL/GAS, HP and Injection.

Figure 7-39 presents the results for all scenarios and variants (blue dot when injection is possible and red cross when not). For S0, the internal rate of return representing the annual profitability of the investment achieves 2.8%. This value is rather low compared to the expectations of an investor.

For the S1 and S2 BIPV scenarios, the IRR reaches up to 4%. For scenario S3, lower values between 1.6-2.3% are obtained.

In terms of NPV, only the S3 scenario with batteries is feasible, presenting positive values between 2-8 CHF/m². However, without considering other parameters (e.g. environmental benefits), results for this scenario are so close to 0 that the investment is difficult to justify if an alternative investment with an annual interest rate of 3% during 30 years is available to the owner.

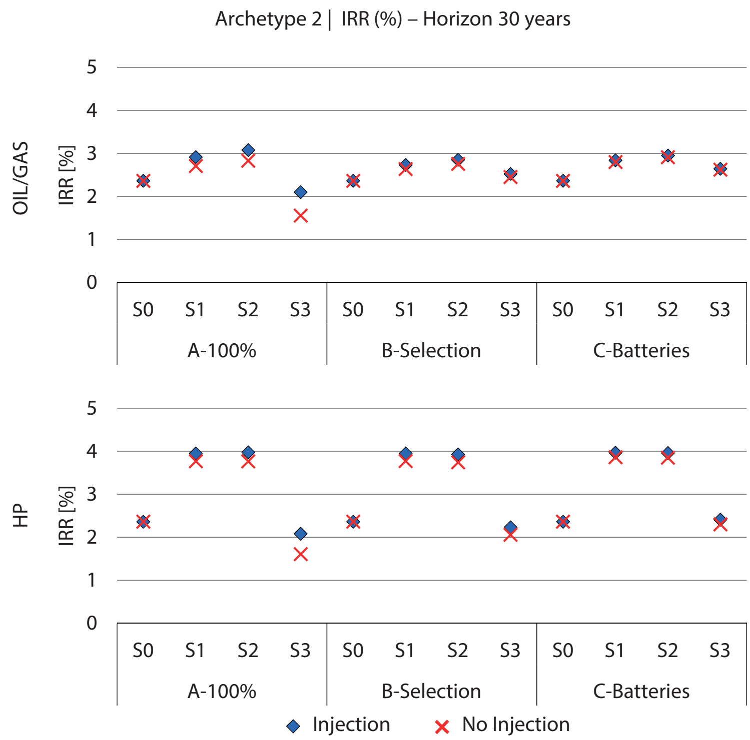


Figure 7-39. Internal rate of return (IRR) for Archetype 2 with a 30-year horizon of each renovation scenario, taking into account the different energy-use scenarios (A, B, and C).

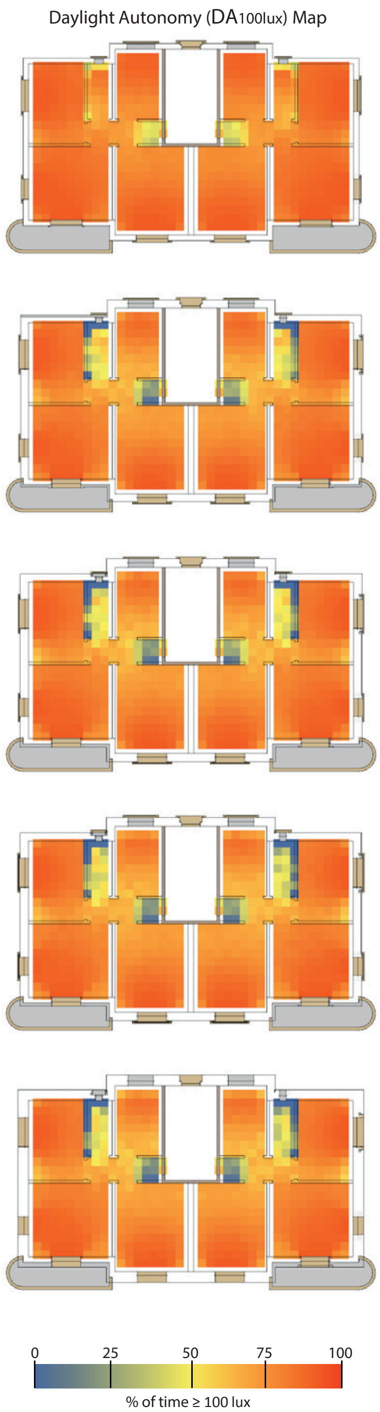
Results for all economic indicators for Archetype 2 are presented in Table 7-17.

LCC	OIL/GAS			HP		
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m2]	830	-	-	-	-	-
NPV* [CHF/m2]	-19	-	-	-	-	-
IRR* [%]	2.4	-	-	-	-	-
DPBT [years]	31	-	-	-	-	-
SPBT [years]	24	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	894	892	916	915	915	956
NPV* [CHF/m2]	62	35	53	236	236	251
IRR* [%]	2.9	2.7	2.8	3.9	3.9	4.0
DPBT [years]	29	30	29	25	25	25
SPBT [years]	22	23	22	20	20	20
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	914	912	936	933	933	972
NPV* [CHF/m2]	94	54	72	250	236	253
IRR* [%]	3.1	2.9	3.0	4.0	3.9	4.0
DPBT [years]	28	29	29	25	25	25
SPBT [years]	22	22	22	20	20	20
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	1162	1032	1056	1284	1218	1247
NPV* [CHF/m2]	-71	-9	8	-82	-60	-24
IRR* [%]	2.1	2.4	2.5	2.1	2.2	2.4
DPBT [years]	32	31	30	32	32	31
SPBT [years]	24	23	23	24	24	23
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	894	892	916	915	915	956
NPV* [CHF/m2]	31	20	46	208	208	234
IRR* [%]	2.7	2.6	2.8	3.8	3.8	3.9
DPBT [years]	30	30	29	26	26	25
SPBT [years]	23	23	22	20	20	20
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	914	912	936	933	933	972
NPV* [CHF/m2]	58	39	65	217	207	235
IRR* [%]	2.9	2.8	2.9	3.8	3.7	3.8
DPBT [years]	29	30	29	26	26	25
SPBT [years]	22	23	22	20	20	20
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	1162	1032	1056	1284	1218	1247
NPV* [CHF/m2]	-169	-24	2	-176	-95	-46
IRR* [%]	1.6	2.4	2.5	1.6	2.0	2.3
DPBT [years]	34	31	30	34	32	31
SPBT [years]	25	23	23	25	24	23

Table 7-17. LCC indicator values obtained for the different scenarios and variants for Archetype 2, with and without injection possibility. * Horizon of 30 years for NPV and IRR calculations.

Indoor comfort

Results shown in Figure 7-40 indicate that the overheating limit of 100 hours/year is respected and the sDA remains above 90% for all scenarios, with a reduction of 6-7% observed after renovation. The DF is somewhat more affected, going from 3.1% to the reference value often used of 2%.



E0 – Current Status

Overheating
OH: 33 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 98% of floor area
DF: 3.1%

S0 – Baseline

Overheating
OH: 36 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 92% of floor area
DF: 2.2%

S1 – BIPV Conservation

Overheating
OH: 70 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 92% of floor area
DF: 2.1%

S2 – BIPV Renovation

Overheating
OH: 47 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 91% of floor area
DF: 2.0%

S3 – BIPV Transformation

Overheating
OH: 58 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 91% of floor area
DF: 2.0%

***OH**: Overheating hours at Ti>26.5°C*
***sDA**: Spatial Daylight Autonomy*
***DF**: Mean Daylight Factor*

** Requirements SIA 180 standard: limit to 100h/year at T>26.5°C*

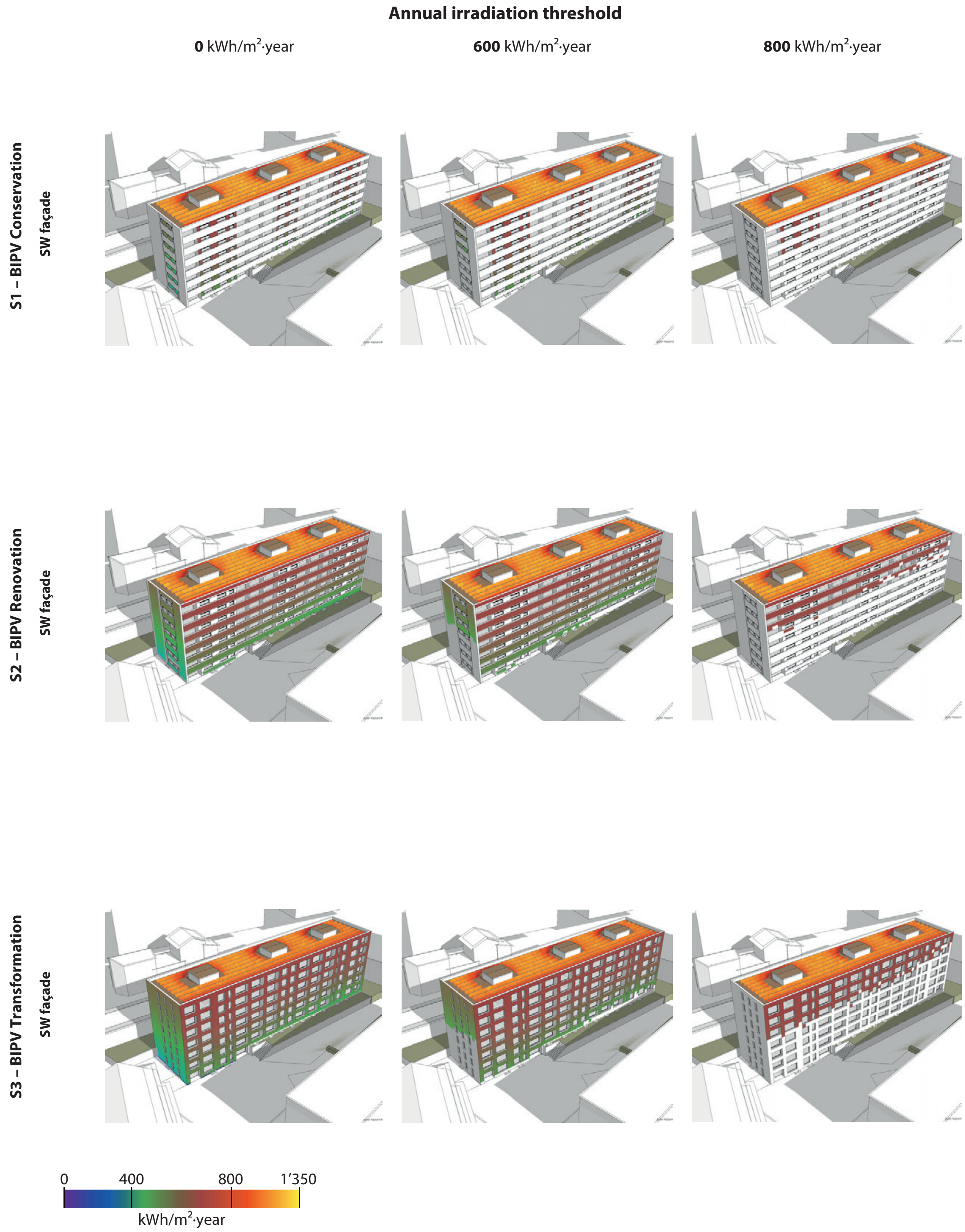
Figure 7-40. Results of the overheating and daylighting study for Archetype 2.

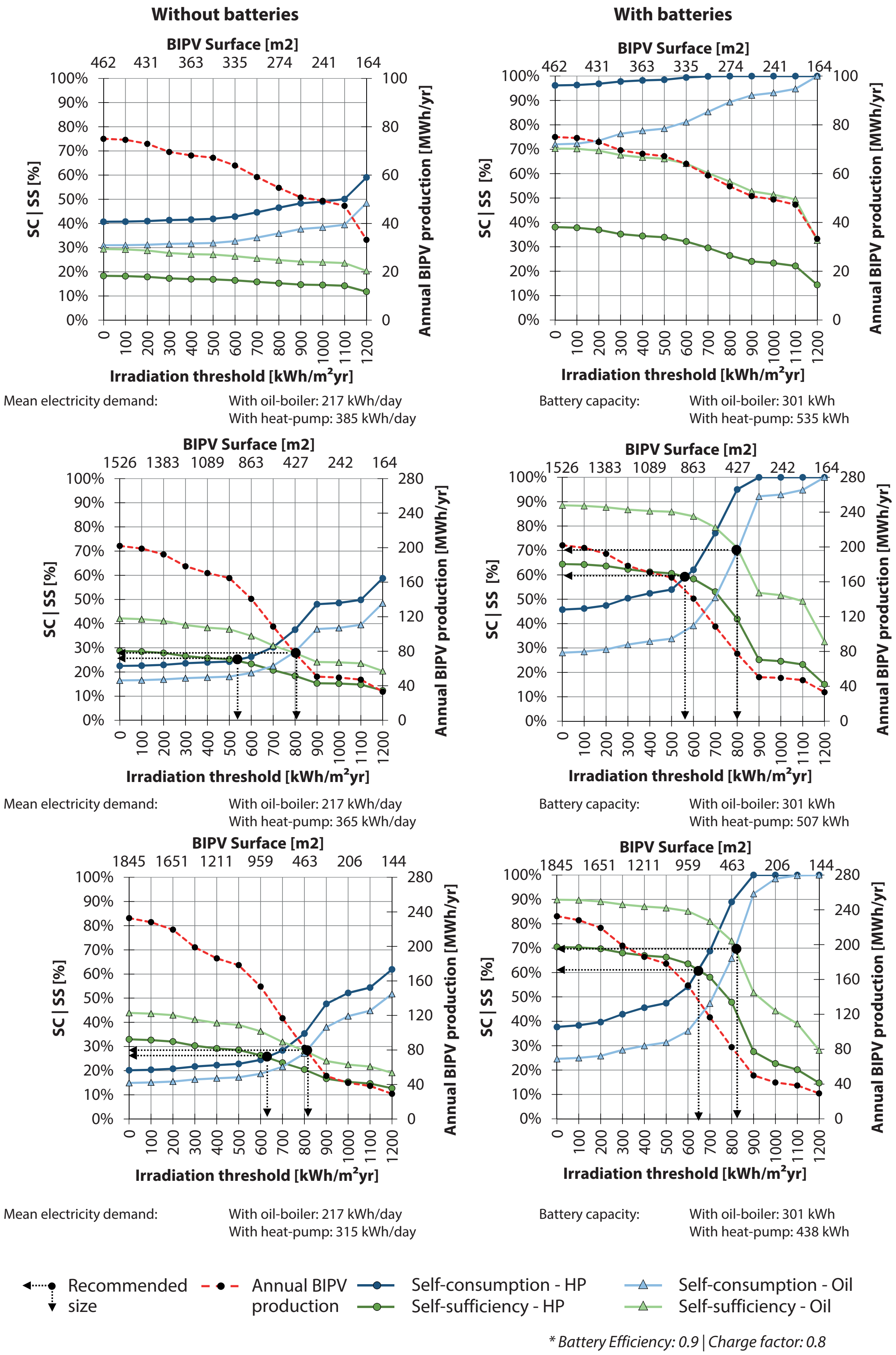
7.3.3. Archetype 3

Sizing of BIPV installation

Figure 7-41 presents the results of the active surfaces selection for Archetype 3.

We observe that for scenario S1, similarly to Archetypes 1 and 2, the SS-SC curves get closer but do not cross at any point due to the dominance of the BAPV installation on the roof (with double-oriented east-west panels) over the façade BIPV, making it difficult to find a better equilibrium between SS and SC.


Annual irradiation threshold
0 kWh/m²·year
600 kWh/m²·year
800 kWh/m²·year
S1 – BIPV Conservation
SW façade
S2 – BIPV Renovation
SW façade
S3 – BIPV Transformation
SW façade
0
400
800
1’350
kWh/m²·year


Without batteries
With batteries
BIPV Surface [m2]
SC | SS [%]
Annual BIPV production [MWh/yr]
Irradiation threshold [kWh/m²yr]
Mean electricity demand:
With oil-boiler: 217 kWh/day
With heat-pump: 385 kWh/day
Battery capacity:
With oil-boiler: 301 kWh
With heat-pump: 535 kWh
Mean electricity demand:
With oil-boiler: 217 kWh/day
With heat-pump: 365 kWh/day
Battery capacity:
With oil-boiler: 301 kWh
With heat-pump: 507 kWh
Mean electricity demand:
With oil-boiler: 217 kWh/day
With heat-pump: 315 kWh/day
Battery capacity:
With oil-boiler: 301 kWh
With heat-pump: 438 kWh
Recommended size
Annual BIPV production
Self-consumption - HP
Self-sufficiency - HP
Self-consumption - Oil
Self-sufficiency - Oil
* Battery Efficiency: 0.9 | Charge factor: 0.8

Daily energy balance | 21 March

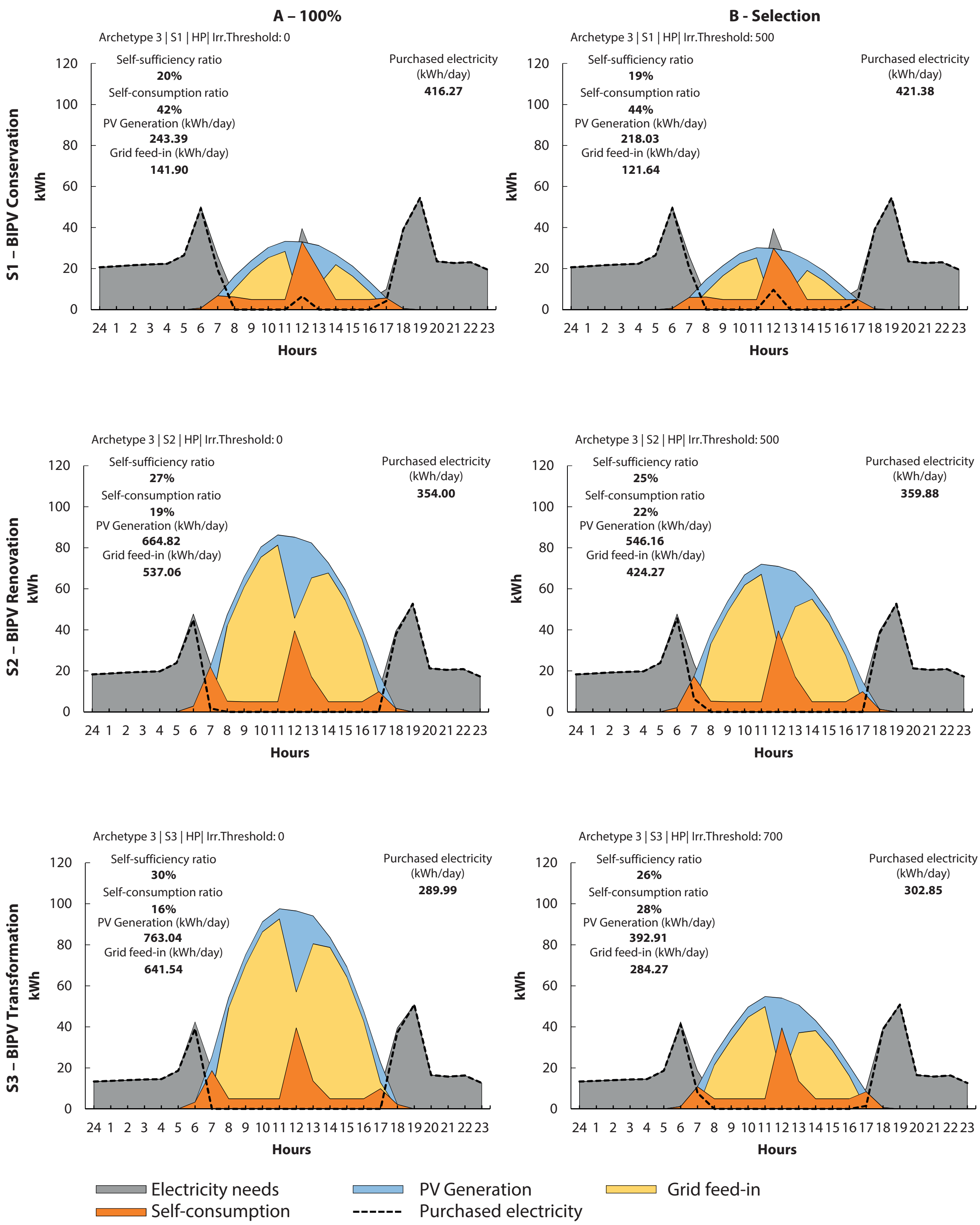


Figure 7-42 shows an example of the daily energy balance (21 March) for Archetype 3. The results present similar values to the previous archetypes, achieving a SS between 19% and 68% and a SC between 16% and 100% (for the scenarios with batteries).

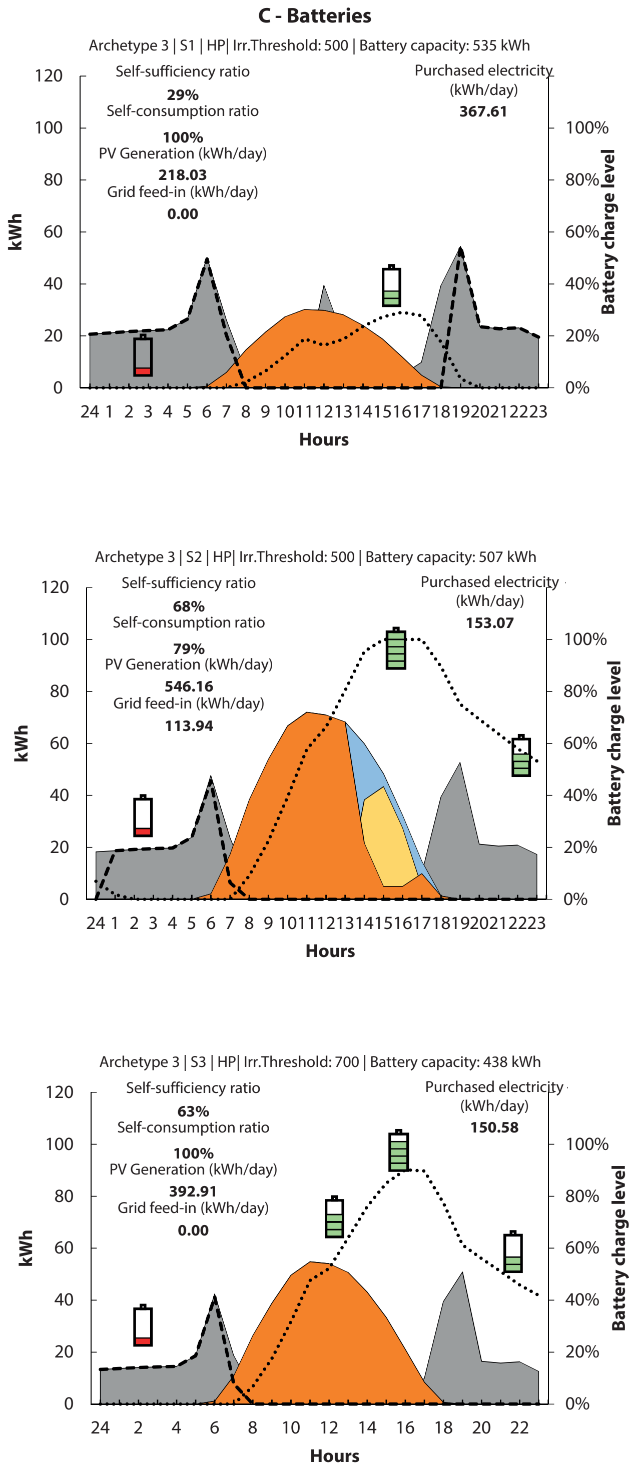


Table 7-18 presents the final values defining all variants for Archetype 3.

In this case, the irradiation values leading to a better equilibrium between SS and SC are between 500 and 800 kWh/m²·year depending on the scenario and variant. For scenario S1, it is difficult to find a good equilibrium due to the dominance of the roof. However, for scenarios S2 and S3 (B-Selection), the SS and SC ratio can achieve about 28% (maintaining the gas-boiler) and 24-29% (implementing a HP), and rise to 60-80% if batteries are considered (C-Batteries).

Active surfaces selection		**OIL/GAS**			**HP**	
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	500	500	0	500	500
SS [%]	29%	27%	73%	18%	17%	35%
SC [%]	31%	32%	86%	41%	42%	100%
Annual production [MWh]	75	67	67	75	67	67
BIPV surfaces [m²]	462	358	358	462	358	358
BIPV installation size [kWp] STC	79	61	61	79	61	67
Battery size [kWh]	-	-	217	-	-	385
S2 – BIPV Renovation	A	B	C	A	B	C
Irr. Threshold [kWh/m²·year]	0	800	800	0	500	500
SS [%]	42%	28%	80%	29%	25%	67%
SC [%]	16%	28%	77%	23%	24%	60%
Annual production [MWh]	202	78	78	202	165	165
BIPV surfaces [m²]	1526	427	427	1526	1046	1046
BIPV installation size [kWp] STC	262	73	73	262	179	179
Battery size [kWh]	-		217	-	-	365
S3 – BIPV Transformation	A	B	C	A	B	C
Irr. Threshold [kWh/m²·year]	0	800	800	0	500	500
SS [%]	44%	28%	81%	33%	29%	71%
SC [%]	15%	27%	73%	20%	23%	61%
Annual production [MWh]	233	81	78	233	178	178
BIPV surfaces [m²]	1845	463	427	1845	1151	1151
BIPV installation size [kWp] STC	316	79	73	316	197	197
Battery size [kWh]	-	-	217	-	-	315

Table 7-18. Values defining different BIPV scenarios and variants for Archetype 3.

Photovoltaic performance

Table 7-19 presents the results of the PV performance indicators for each BIPV scenario of Archetype 3. In terms of energy (EPBT) and GHG emission (GPBT) payback times, all values are lower than 25 years (performance warranty period of the PV modules). The higher values are observed for the C-Batteries option and are mainly due to the environmental impact of the batteries.

PV performance	OIL/GAS			HP		
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/$kWh_{e\text{-}pv}$]	0.049	0.056	0.139	0.049	0.056	0.139
NRE_{PV} [kWh_{NRE}/ $kWh_{e\text{-}pv}$]	0.158	0.136	0.227	0.158	0.136	0.297
CCF_{PV} [$kgCO_2$/ $kWh_{e\text{-}pv}$]	0.041	0.036	0.057	0.041	0.036	0.073
$EPBT_{PV}$ [years]	3.3	2.8	4.7	3.3	2.8	6.1
$GPBT_{PV}$ [years]	12.0	10.4	16.5	12.0	10.4	21.2
Energy yield [$kWh_{e\text{-}pv}$/kWh_p]	948	1096		948	1096	
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/$kWh_{e\text{-}pv}$]	0.080	0.070	0.140	0.080	0.075	0.106
NRE_{PV} [kWh_{NRE}/ $kWh_{e\text{-}pv}$]	0.194	0.141	0.219	0.194	0.163	0.224
CCF_{PV} [$kgCO_2$/ $kWh_{e\text{-}pv}$]	0.051	0.037	0.055	0.051	0.042	0.057
$EPBT_{PV}$ [years]	4.0	2.9	4.5	4.0	3.4	4.6
$GPBT_{PV}$ [years]	14.7	10.7	16.0	14.7	12.4	16.6
Energy yield [$kWh_{e\text{-}pv}$/kWh_p]	773	1061		773	920	
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/$kWh_{e\text{-}pv}$]	0.085	0.072	0.139	0.085	0.076	0.105
NRE_{PV} [kWh_{NRE}/ $kWh_{e\text{-}pv}$]	0.203	0.146	0.221	0.203	0.166	0.215
CCF_{PV} [$kgCO_2$/ $kWh_{e\text{-}pv}$]	0.053	0.038	0.055	0.053	0.043	0.055
$EPBT_{PV}$ [years]	4.2	3.0	4.6	4.2	3.4	4.4
$GPBT_{PV}$ [years]	15.5	11.1	16.2	15.5	12.6	16.0
Energy yield [$kWh_{e\text{-}pv}$/kWh_p]	736	1025		736	904	

Table 7-19. PV performance indicator values obtained for the different BIPV scenarios and variants for Archetype 3.

Energy balance (operational phase)

The resulting power required for heating (Figure 7-43) is reduced progressively according to the intensity of the intervention from 483 kW (for E0) to 165, 147, 137 and 117 kW for S0, S1, S2 and S3 respectively.

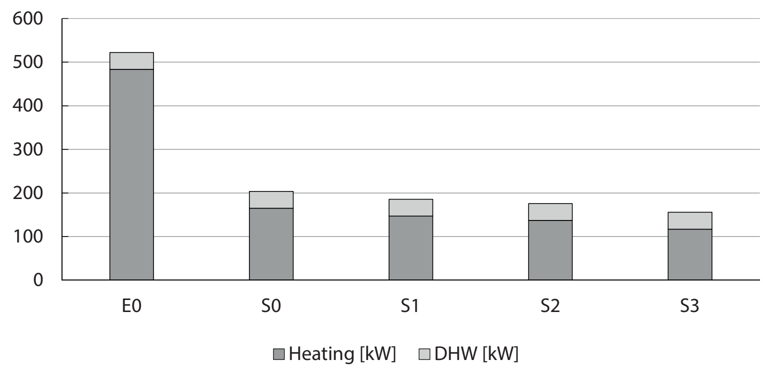
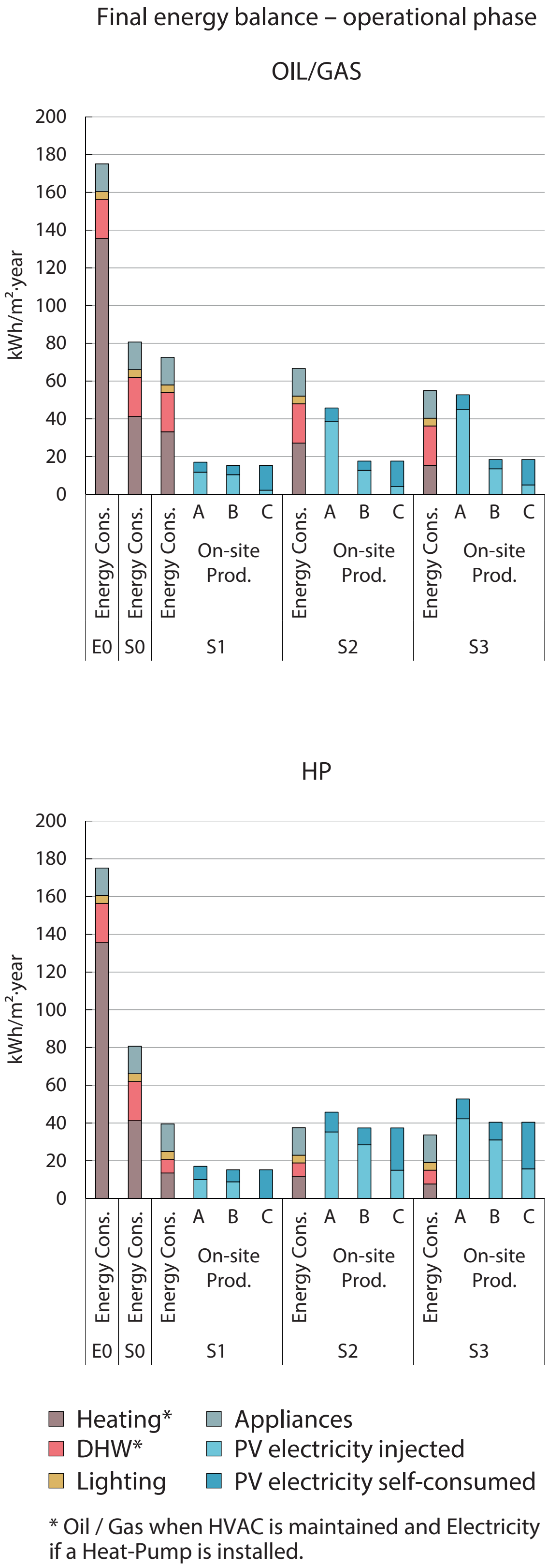


Figure 7-43. Power required for the HVAC system (heating and DHW), Archetype 3.

From the final energy balance in Figure 7-44, we observe energy savings of 53% due only to passive strategies complying with minimum legal requirement (S0). For scenarios S1 to S3, total savings range from 58% to 68% when maintaining the gas-boiler, and go up to 77% (S1), 78% (S2) and 80% (S3) when replacing the existing system by a HP. In the latter case, scenarios S2 and S3 lead to a positive energy building considering the amount of electricity produced on-site.

In terms of environmental impact, some scenarios respect both targets of the 2’000-Watt Society, especially S3 and scenarios with replacement of the HVAC system. In the case of no injection, only S2 and S3, especially with the batteries option, fulfil the objectives.



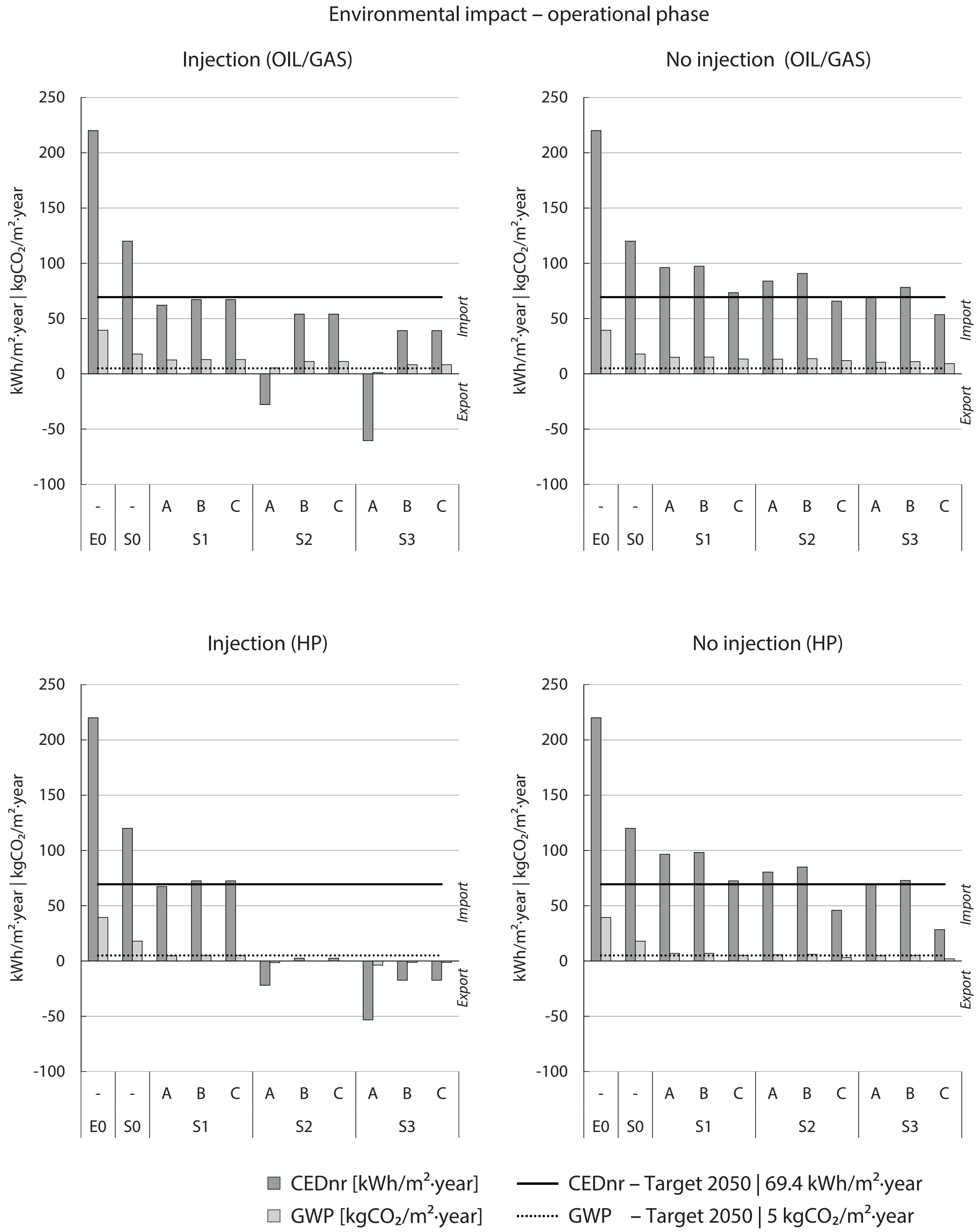


Figure 7-44. Final energy balance, non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP) for the operational phase of the Archetype 3, for each renovation scenario and energy-use scenario (A-100%, B-Selection and C-Batteries), with or without replacing the existing HVAC system and considering or not the possibility to inject into the grid.

Results for all indicators of this group are presented in Table 7-20.

Operational phase	OIL/GAS			HP		
E0 - Current Status						
Consumption [kWh/m²·year]						
Gas		156			-	
Electricity		19				
CED_{nr} [kWh_{NRE}/m²·year]		213				
GWP [$kgCO_2$/m²·year]		38				
HVAC Power needed [kW]		483				
S0 - Baseline						
Consumption [kWh/m²·year]						
Gas		62			-	
Electricity		19				
CED_{nr} [kWh_{NRE}/m²·year]		113				
GWP [$kgCO_2$/m²·year]		16				
HVAC Power needed [kW]		165				
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m²·year]						
Gas		54			-	
Electricity		19			39	
PVSC [kWh_{e-pv}/m²·year]	5	5	13	7	6	15
PVI [kWh_{e-pv}/m²·year]	12	10	2	10	9	0
SS | SC [%]	29 | 31	27 | 32	73 | 86	18 | 41	17 | 42	35 | 100
CED_{nr} [kWh_{NRE}/m²·year]	62	67	67	67	73	73
GWP [$kgCO_2$/m²·year]	13	13	13	5	5	5
HVAC Power needed [kW]			147			
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m²·year]						
Gas		48			-	
Electricity		19			38	
PVSC [kWh_{e-pv}/m²·year]	7	5	14	11	9	22
PVI [kWh_{e-pv}/m²·year]	38	13	4	35	28	15
SS | SC [%]	42 | 16	28 | 28	80 | 77	29 | 23	25 | 24	67 | 60
CED_{nr} [kWh_{NRE}/m²·year]	-28	54	54	-22	3	3
GWP [$kgCO_2$/m²·year]	5	11	11	-2	0	0
HVAC Power needed [kW]			137			
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m²·year]						
Gas		36			-	
Electricity		19			34	
PVSC [kWh_{e-pv}/m²·year]	8	5	13	11	9	25
PVI [kWh_{e-pv}/m²·year]	45	13	5	42	31	16
SS | SC [%]	44 | 15	28 | 27	81 | 73	33 | 20	29 | 23	71 | 61
CED_{nr} [kWh_{NRE}/m²·year]	-60	39	39	-53	-17	-17
GWP [$kgCO_2$/m²·year]	1	8	8	-4	-1	-1
HVAC Power needed [kW]			117			

Table 7-20. Final energy balance (operational phase) indicator values obtained for the different scenarios and variants for Archetype 3, taking into account the injection of the electricity overproduction into the grid. Negative values correspond to positive energy scenarios (the energy produced is higher than the consumption).

Life-Cycle Assessment (LCA)

This section shows the global LCA results for Archetype 3, considering both the operational phase and the environmental impact of the construction materials. Figure 7-45 and Figure 7-46 graphically show the results for all scenarios and variants including with or without injection possibility. In addition, Table 7-21 presents a summary of the results including the energy payback time (EPBT) and the GHG emissions payback time (GPBT).

Considering the injection of the electricity overproduced (Figure 7-45), if the gas-boiler is maintained, none of the scenarios respect both limits (CEDnr and GWP). However, when the gas-boiler is replaced by a HP, the three BIPV scenarios comply with the requirements of the 2'000-Watt Society (310 MJ/m^2·year and 10 $kgCO_2/m^2$·year). If the injection into the grid is not available (Figure 7-46), only BIPV scenarios (S1 to S3 replacing the gas-boiler) achieve both targets.

In terms of payback times (Table 7-21), values obtained are between 2.9-3.9 years (for EPBT) and 4.1-8.0 years (for GPBT) if the injection into the grid is possible, and slightly higher, between 3.6-5.9 years (for EPBT) and 2.1-9.2 years (for GPBT) without injection.

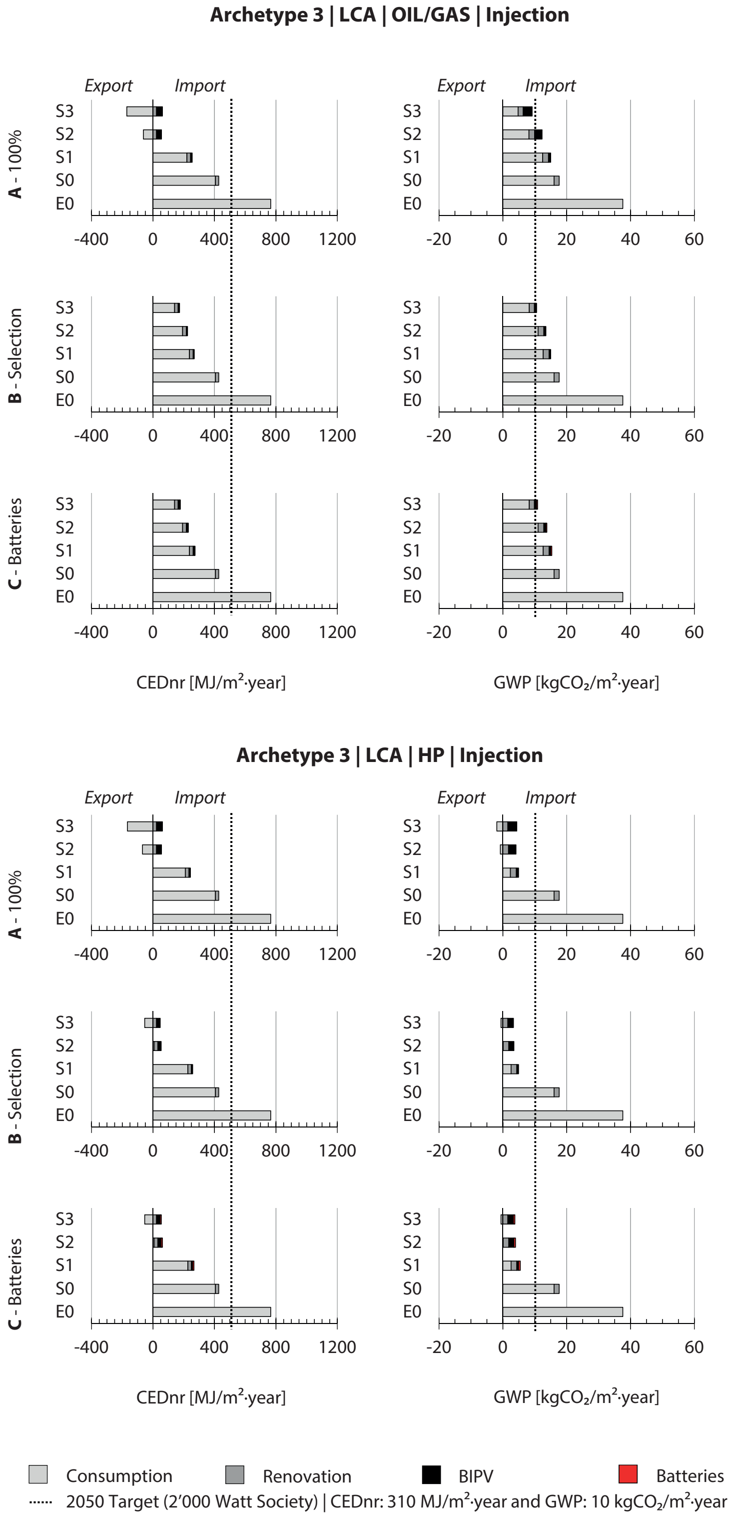


Figure 7-45. LCA results for Archetype 3 (injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

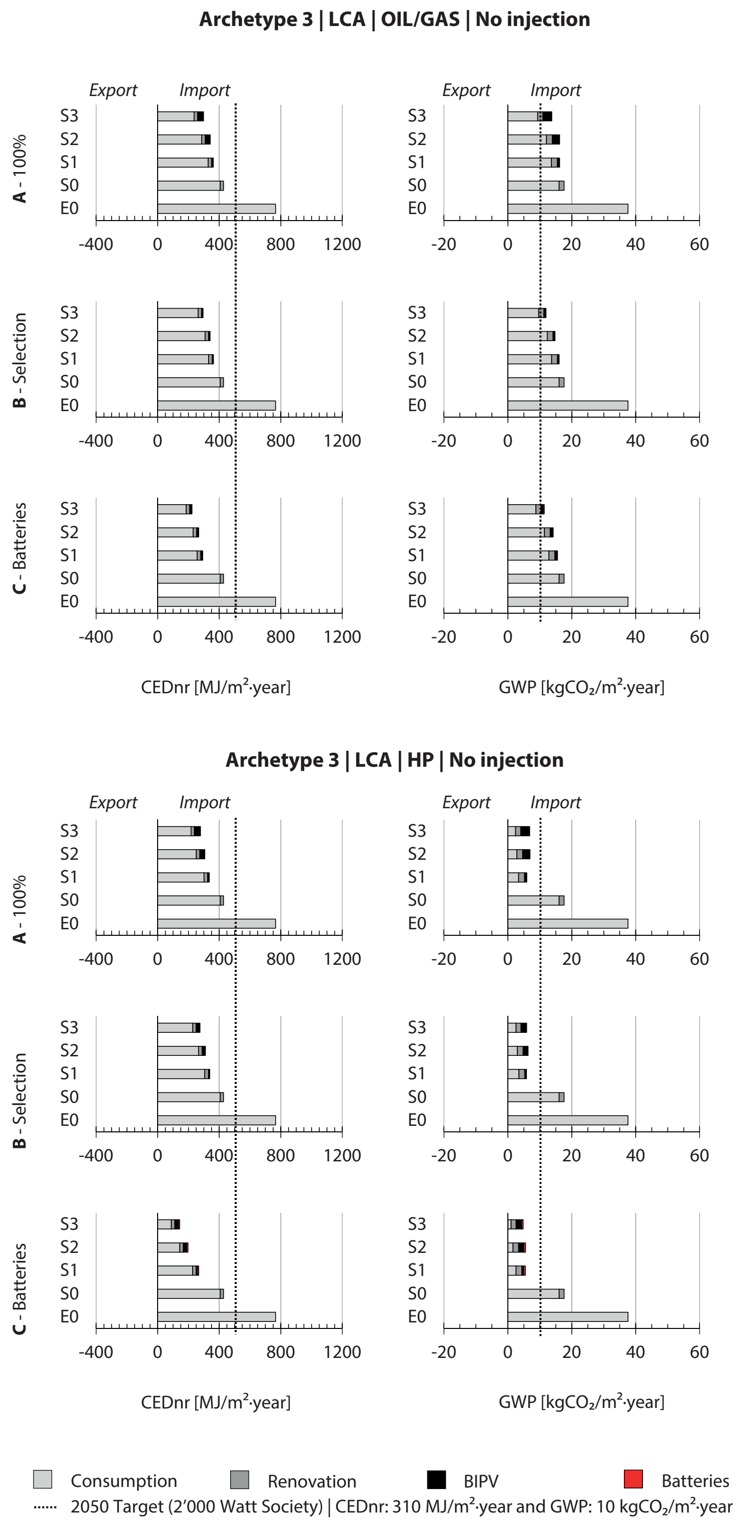


Figure 7-46. LCA results for Archetype 3 (self-consumption approach without injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

LCA	OIL/GAS			HP		
E0 – Current Status	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	766	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	38	-	-	-	-	-
EPBT [years]	-	-	-	-	-	-
GPBT [years]	-	-	-	-	-	-
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	428	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	18	-	-	-	-	-
EPBT [years]	3.6	-	-	-	-	-
GPBT [years]	4.4	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	252	267	272	243	257	266
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	15	15	15	5	5	6
EPBT [years]	3.4	3.4	3.9	3.5	3.4	4.4
GPBT [years]	5.9	5.6	6.4	4.3	4.1	5.1
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	-15	223	228	-20	49	57
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	12	13	14	3	3	4
EPBT [years]	3.4	3.1	3.6	3.5	3.2	3.9
GPBT [years]	8.0	5.4	6.1	6.2	5.3	6.1
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	-118	171	176	-113	-12	-5
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	9	11	11	2	3	3
EPBT [years]	3.4	2.9	3.4	3.4	3.1	3.6
GPBT [years]	7.6	4.6	5.2	6.4	5.1	5.8
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	359	361	291	334	337	266
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	16	16	16	6	6	6
EPBT [years]	4.3	4.1	4.1	4.2	4.0	4.4
GPBT [years]	6.2	5.9	6.4	4.4	4.2	5.1
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	334	338	265	300	306	193
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	16	15	14	7	6	5
EPBT [years]	5.9	3.9	3.9	5.7	4.9	4.7
GPBT [years]	9.2	5.7	6.2	6.9	5.7	6.4
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	289	293	221	270	270	138
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	14	12	11	7	6	5
EPBT [years]	5.9	3.6	3.6	5.8	4.7	4.4
GPBT [years]	5.9	2.1	2.7	5.1	2.3	3.1

Table 7-21. LCA indicator values obtained for the different scenarios and variants for Archetype 3, with and without injection possibility. Values in bold respect the 2050 targets (2’000-Watt Society).

Life-cycle cost (LCC)

Figure 7-47 presents the cumulative energy consumption cost during a horizon of 50 years. The SPBT of BIPV scenarios are lower by about 5 years compared to S0.

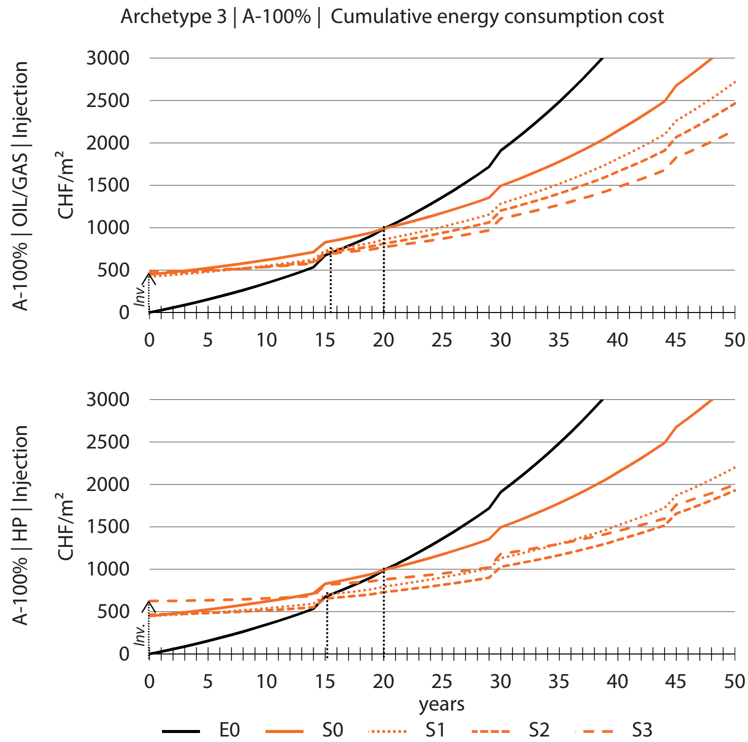


Figure 7-47. Cumulative energy consumption cost for Archetype 3, considering A-100%, OIL/GAS, HP and Injection.

From Figure 7-48, we observe that for S0, the IRR achieves 4.1%, a value quite high compared to the expectations of an investor, and mainly caused by the low performance of the current status (E0) situation, typical of buildings from the 70s.

For all BIPV scenarios, the IRR is higher, achieving up to 7.5% without exceptions. The highest value occurs in scenario S3, replacing the gas-boiler and including batteries, mainly because the roof installation allows making an efficient use of the batteries.

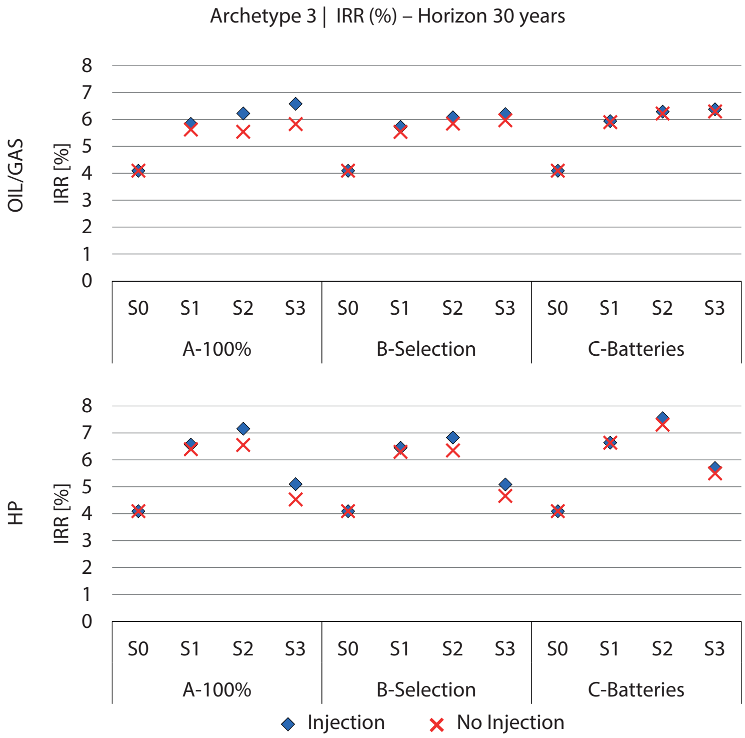


Figure 7-48. Internal rate of return (IRR) for Archetype 3 with a 30-year horizon of each renovation scenario, taking into account the different energy-use scenarios (A, B, and C).

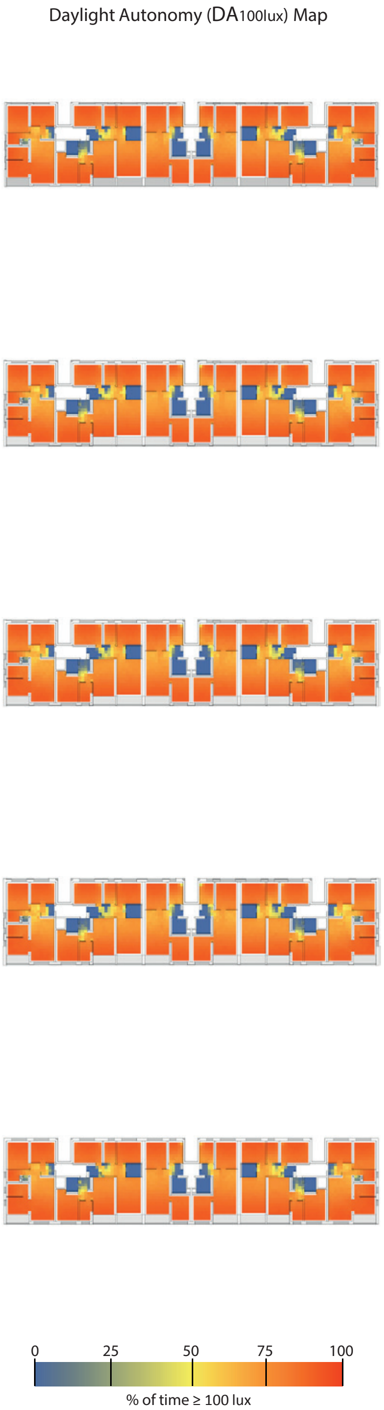
Results for all economic indicators for Archetype 3 are presented in Table 7-22.

LCC	OIL/GAS			HP		
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m2]	448	-	-	-	-	-
NPV* [CHF/m2]	84	-	-	-	-	-
IRR* [%]	4.1	-	-	-	-	-
DPBT [years]	26	-	-	-	-	-
SPBT [years]	20	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	421	424	449	446	449	474
NPV* [CHF/m2]	221	212	247	305	295	334
IRR* [%]	5.8	5.7	5.9	6.6	6.4	6.6
DPBT [years]	21	21	21	19	19	19
SPBT [years]	16	16	16	15	15	15
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	456	427	452	464	468	479
NPV* [CHF/m2]	266	245	283	367	339	432
IRR* [%]	6.2	6.1	6.3	7.2	6.8	7.5
DPBT [years]	20	20	20	18	18	17
SPBT [years]	15	16	16	14	15	14
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	481	459	484	624	607	632
NPV* [CHF/m2]	315	275	311	223	219	308
IRR* [%]	6.6	6.2	6.4	5.1	5.1	5.7
DPBT [years]	19	20	20	23	23	21
SPBT [years]	15	16	15	18	18	17
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	421	424	449	446	449	474
NPV* [CHF/m2]	205	199	244	291	283	334
IRR* [%]	5.6	5.5	5.9	6.4	6.3	6.6
DPBT [years]	22	22	21	20	20	19
SPBT [years]	17	17	16	15	16	15
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	456	427	452	464	468	479
NPV* [CHF/m2]	213	228	277	317	299	411
IRR* [%]	5.5	5.8	6.2	6.6	6.3	7.3
DPBT [years]	22	21	20	19	20	18
SPBT [years]	17	16	16	15	16	14
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	481	459	484	624	607	632
NPV* [CHF/m2]	252	256	304	164	175	286
IRR* [%]	5.8	6.0	6.3	4.5	4.7	5.5
DPBT [years]	21	21	20	25	24	22
SPBT [years]	16	16	16	19	19	17

Table 7-22. LCC indicator values obtained for the different scenarios and variants for Archetype 3, with and without injection possibility. * Horizon of 30 years for NPV and IRR calculations.

Indoor comfort

Results shown in Figure 7-49 indicate that the overheating limit of 100 hours/year is respected and the sDA remains above 80% for all scenarios. For S0 to S2, a reduction of sDA of about 1-2% is observed. For S3, the sDA value remains at 89% (as for E0) due to the increase in the windows size. However, the DF is lower than for E0 (but still well above 2%) due to the greater depth of the window opening (external insulation with ventilated facade).



E0 – Current Status

Overheating
OH: 20 hours/year*

Daylighting
$sDA_{100lux,\,50\%}$: 89% of floor area
DF: 3.3%

S0 – Baseline

Overheating
OH: 16 hours/year*

Daylighting
$sDA_{100lux,\,50\%}$: 88% of floor area
DF: 2.7%

S1 – BIPV Conservation

Overheating
OH: 12 hours/year*

Daylighting
$sDA_{100lux,\,50\%}$: 88% of floor area
DF: 2.6%

S2 – BIPV Renovation

Overheating
OH: 16 hours/year*

Daylighting
$sDA_{100lux,\,50\%}$: 87% of floor area
DF: 2.5%

S3 – BIPV Transformation

Overheating
OH: 25 hours/year*

Daylighting
$sDA_{100lux,\,50\%}$: 89% of floor area
DF: 3.1%

***OH**: Overheating hours at Ti>26.5°C*
***sDA**: Spatial Daylight Autonomy*
***DF**: Mean Daylight Factor*

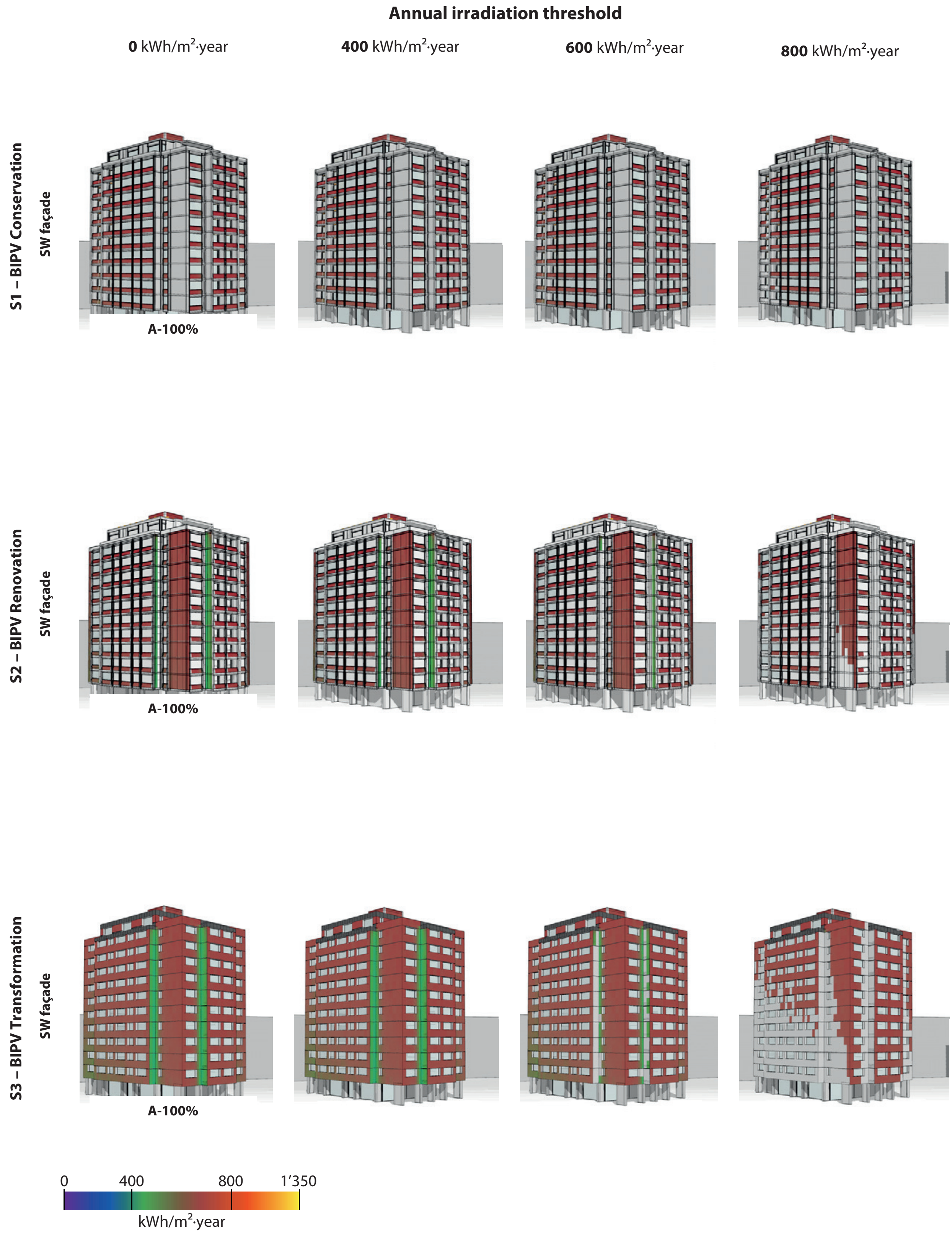
** Requirements SIA 180 standard: limit to 100h/year at T>26.5°C*

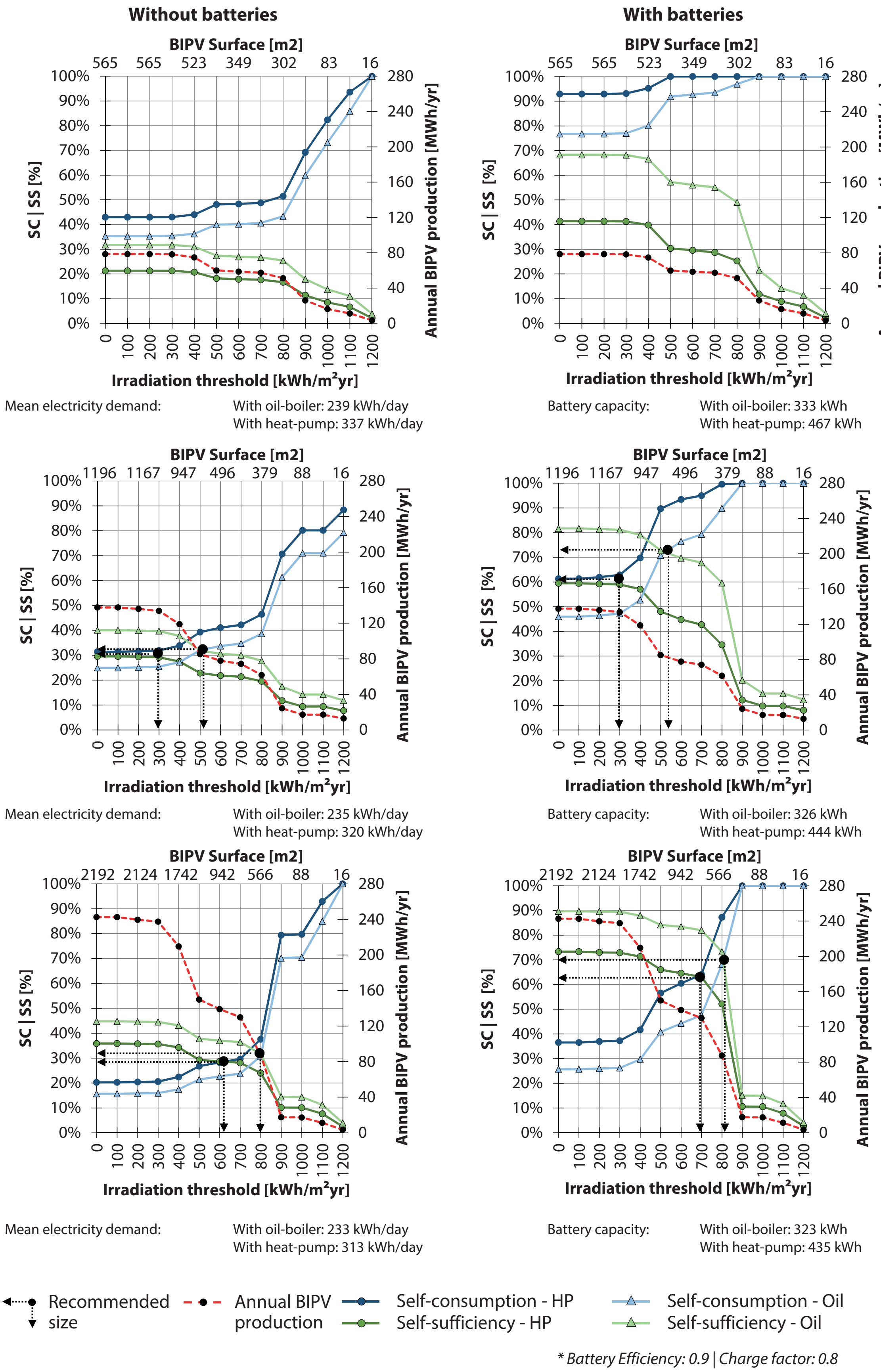
Figure 7-49. Results of the overheating and daylighting study for Archetype 3.

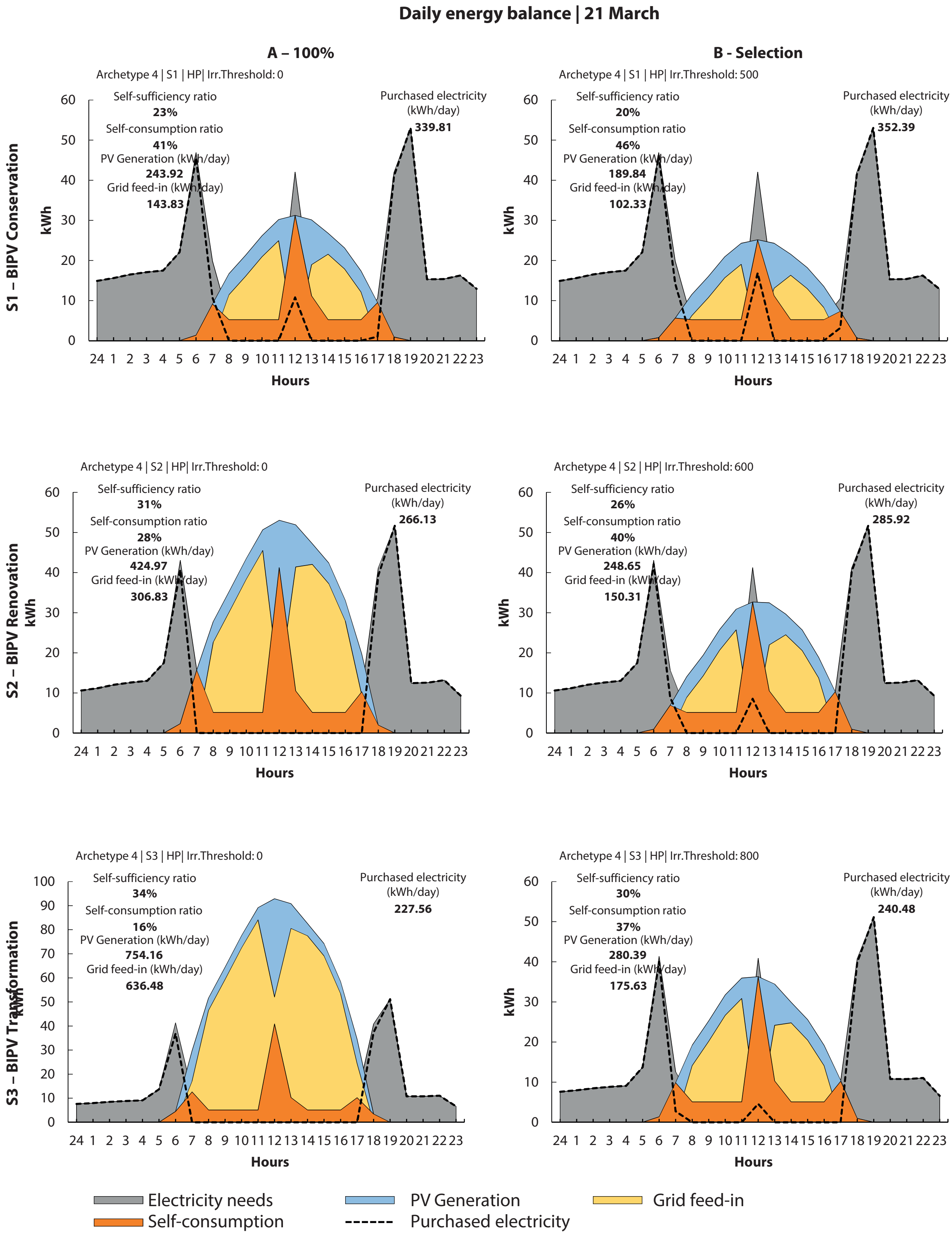
7.3.4. Archetype 4

Sizing of BIPV installation

Figure 7-50 presents the results of the active surfaces selection for Archetype 4. For this archetype, mainly due to the large façade potential, the best equilibrium between SS and SC is achieved with 300-800 kWh/m^2·year for both maintaining or replacing the gas-boiler. Here again, the SS-SC curves remain parallel for scenario S1, in this case with lower irradiation threshold (between 0 to 300 kWh/m^2·year) due to the dominance of the façade surfaces (contrary to the Archetype 3). In the same way, curves do not cross at any precise point because no combination of the remaining surfaces allows to achieve a complete equilibrium between SS and SC.


Annual irradiation threshold
0 kWh/m²·year
400 kWh/m²·year
600 kWh/m²·year
800 kWh/m²·year
S1 – BIPV Conservation
SW façade
A-100%
S2 – BIPV Renovation
SW façade
A-100%
S3 – BIPV Transformation
SW façade
A-100%
0
400
800
1’350
kWh/m²·year

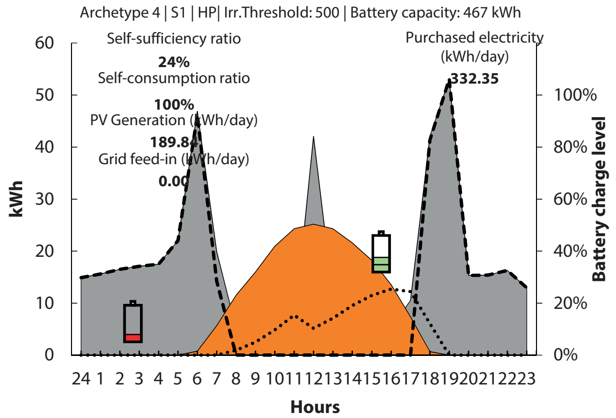

Without batteries
With batteries
BIPV Surface [m2]
SC | SS [%]
Annual BIPV production [MWh/yr]
Irradiation threshold [kWh/m²yr]
Mean electricity demand: With oil-boiler: 239 kWh/day With heat-pump: 337 kWh/day
Battery capacity: With oil-boiler: 333 kWh With heat-pump: 467 kWh
Mean electricity demand: With oil-boiler: 235 kWh/day With heat-pump: 320 kWh/day
Battery capacity: With oil-boiler: 326 kWh With heat-pump: 444 kWh
Mean electricity demand: With oil-boiler: 233 kWh/day With heat-pump: 313 kWh/day
Battery capacity: With oil-boiler: 323 kWh With heat-pump: 435 kWh
Recommended size
Annual BIPV production
Self-consumption - HP
Self-sufficiency - HP
Self-consumption - Oil
Self-sufficiency - Oil
* Battery Efficiency: 0.9 | Charge factor: 0.8

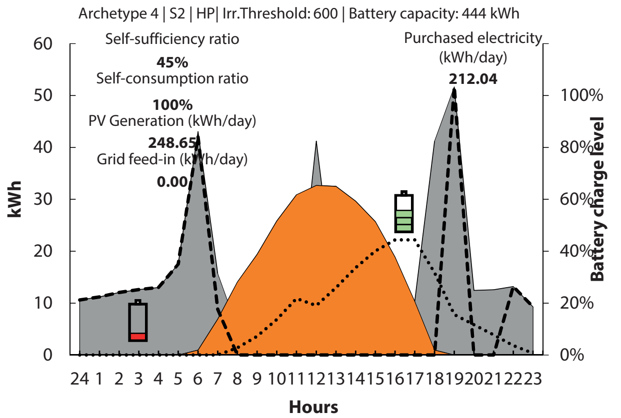


Daily energy balance | 21 March
A – 100%
B - Selection
S1 – BIPV Conservation
Archetype 4 | S1 | HP| Irr.Threshold: 0
Self-sufficiency ratio
23%
Self-consumption ratio
41%
PV Generation (kWh/day)
243.92
Grid feed-in (kWh/day)
143.83
Purchased electricity
(kWh/day)
339.81
Archetype 4 | S1 | HP| Irr.Threshold: 500
Self-sufficiency ratio
20%
Self-consumption ratio
46%
PV Generation (kWh/day)
189.84
Grid feed-in (kWh/day)
102.33
Purchased electricity
(kWh/day)
352.39
S2 – BIPV Renovation
Archetype 4 | S2 | HP| Irr.Threshold: 0
Self-sufficiency ratio
31%
Self-consumption ratio
28%
PV Generation (kWh/day)
424.97
Grid feed-in (kWh/day)
306.83
Purchased electricity
(kWh/day)
266.13
Archetype 4 | S2 | HP| Irr.Threshold: 600
Self-sufficiency ratio
26%
Self-consumption ratio
40%
PV Generation (kWh/day)
248.65
Grid feed-in (kWh/day)
150.31
Purchased electricity
(kWh/day)
285.92
S3 – BIPV Transformation
Archetype 4 | S3 | HP| Irr.Threshold: 0
Self-sufficiency ratio
34%
Self-consumption ratio
16%
PV Generation (kWh/day)
754.16
Grid feed-in (kWh/day)
636.48
Purchased electricity
(kWh/day)
227.56
Archetype 4 | S3 | HP| Irr.Threshold: 800
Self-sufficiency ratio
30%
Self-consumption ratio
37%
PV Generation (kWh/day)
280.39
Grid feed-in (kWh/day)
175.63
Purchased electricity
(kWh/day)
240.48
kWh
Hours
Electricity needs
Self-consumption
PV Generation
Purchased electricity
Grid feed-in

Figure 7-51 shows an example of the daily energy balance (21 March) for the Archetype 4. The achieved SS and SC are respectively between 20-71% and 16%-100% (for the scenarios with batteries).

C - Batteries





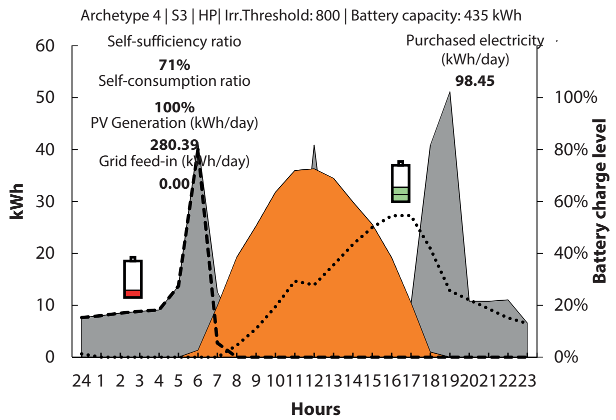


Table 7-26 presents the final values defining all variants for Archetype 4.

In this case, the irradiation values leading to a better trade-off between SS and SC are between 300 and 800 kWh/m²·year depending on the scenario and variant, putting in evidence the dominance of the available surfaces on façades compared to the roof.

For this archetype, all scenarios achieve a good equilibrium (B-Selection), with the SS and SC of about 32% (maintaining the gas-boiler) and 23-39% (implementing a HP), and falling within a larger range if batteries are considered (C-Batteries).

Active surfaces selection		**OIL/GAS**			**HP**	
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	300	300	0	300	300
SS [%]	32%	32%	68%	21%	21%	41%
SC [%]	35%	35%	77%	43%	43%	93%
Annual production [MWh]	79	78	78	79	75	75
BIPV surfaces [m²]	565	562	562	565	523	523
BIPV installation size [kWp] STC	97	96	96	97	90	75
Battery size [kWh]	-	-	498	-	-	701
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	500	500	0	300	300
SS [%]	40%	32%	73%	30%	23%	48%
SC [%]	25%	32%	71%	31%	39%	90%
Annual production [MWh]	138	85	85	138	134	134
BIPV surfaces [m²]	1196	565	565	1196	1131	1131
BIPV installation size [kWp] STC	205	97	97	205	194	194
Battery size [kWh]	-		498	-	-	665
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	800	800	0	600	700
SS [%]	45%	32%	73%	36%	29%	63%
SC [%]	16%	31%	68%	20%	28%	64%
Annual production [MWh]	243	87	85	243	139	139
BIPV surfaces [m²]	2192	566	565	2192	942	942
BIPV installation size [kWp] STC	376	97	97	376	161	161
Battery size [kWh]	-	-	498	-	-	653

Table 7-23. Values defining different BIPV scenarios and variants for Archetype 4.

Photovoltaic performance

From Table 7-24, showing the different PV performance indicators, we observe that in terms of carbon content, scenarios with batteries have the highest values. However, only scenario (S3, C-Batteries) with 0.108 kgCO_2/ kWhe-pv is higher than the grid, leading to a GPBT of 31 years. Energy yield values reflect the dominance of the active surfaces on façades, with values from 646 to 901 kWhe-pv/kWhp.

Table 7-24. PV performance indicator values obtained for the different BIPV scenarios and variants for Archetype 4.

PV performance	**OIL/GAS**			**HP**		
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.085	0.083	0.173	0.085	0.080	0.196
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.184	0.184	0.362	0.184	0.179	0.441
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.048	0.048	0.089	0.048	0.047	0.108
$EPBT_{PV}$ [years]	3.8	3.8	7.5	3.8	3.7	9.1
$GPBT_{PV}$ [years]	14.0	14.0	26.1	14.0	13.7	31.4
Energy yield [kWh_{e-pv}/kWh_p]	812	813		812	834	
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.101	0.073	0.144	0.101	0.089	0.151
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.223	0.170	0.334	0.223	0.217	0.355
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.058	0.044	0.082	0.058	0.057	0.089
$EPBT_{PV}$ [years]	4.6	3.5	6.9	4.6	4.5	7.3
$GPBT_{PV}$ [years]	16.9	13.0	24.0	16.9	16.5	25.9
Energy yield [kWh_{e-pv}/kWh_p]	672	879		672	691	
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.103	0.066	0.135	0.103	0.068	0.126
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.232	0.166	0.321	0.232	0.174	0.305
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.061	0.043	0.079	0.061	0.045	0.076
$EPBT_{PV}$ [years]	4.8	3.4	6.6	4.8	3.6	6.3
$GPBT_{PV}$ [years]	17.6	12.6	23.2	17.6	13.2	22.1
Energy yield [kWh_{e-pv}/kWh_p]	646	901		646	861	

Energy balance (operational phase)

The power required for heating (Figure 7-52) drops from 460 kW (for E0) to 194, 131, 116 and 103 kW for S0, S1, S2 and S3 respectively.

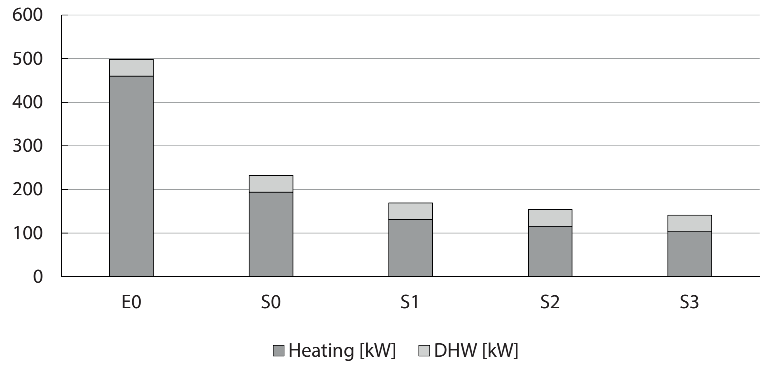
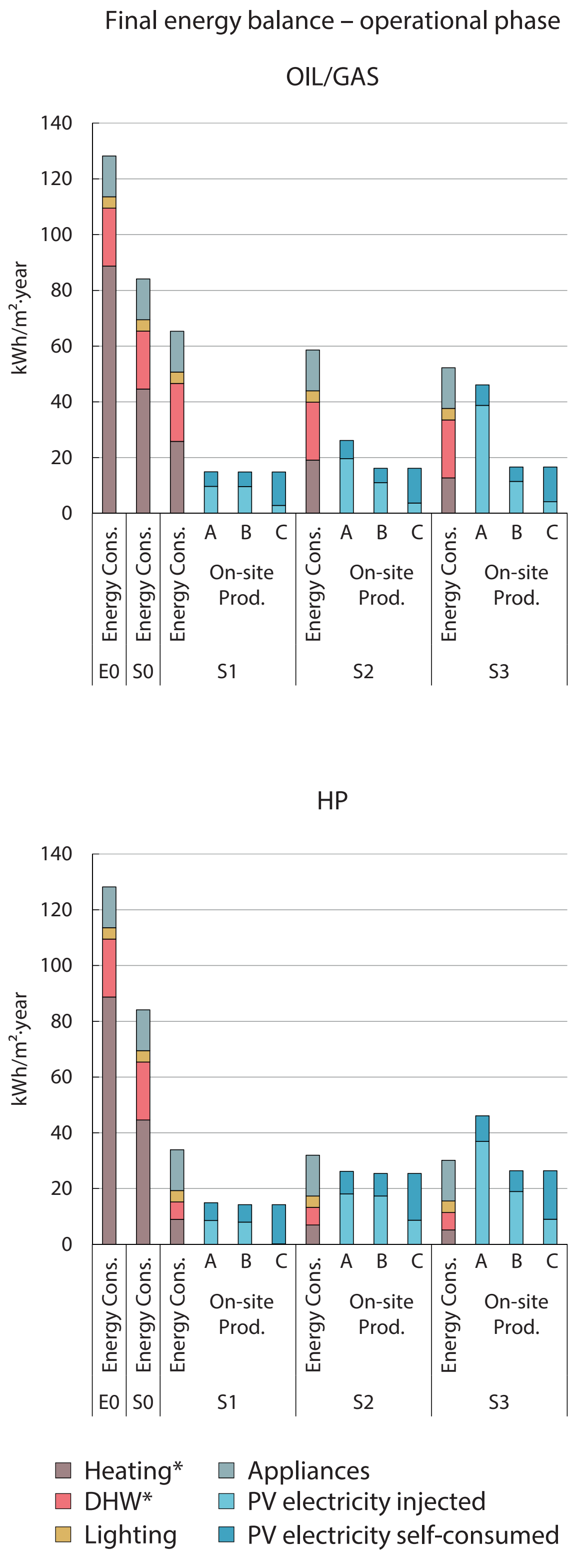


Figure 7-52. Power required for the HVAC system (heating and DHW), Archetype 4.

The final energy balance presented in Figure 7-53 shows that scenario S0 reaches 34% of energy savings, while scenarios S1 to S3 lead to total savings ranging from 49% to 59% when maintaining the oil-boiler and over 70% with a HP. In addition, considering the PV production, scenario S3, A-100% becomes a positive energy building that produces more energy than it needs over an annual balance.

The CEDnr and GWP environmental impact targets for energy consumption (operational phase) are respected by all scenarios when replacing the existing oil-boiler, and by scenarios S2 and S3 with the option A-100%, OIL/GAS. Scenarios with batteries help achieve both targets when no injection is possible. In this case study, if the existing oil-boiler is replaced, all options of scenario S3 fulfil the objectives.



* Oil / Gas when HVAC is maintained and Electricity if a Heat-Pump is installed.

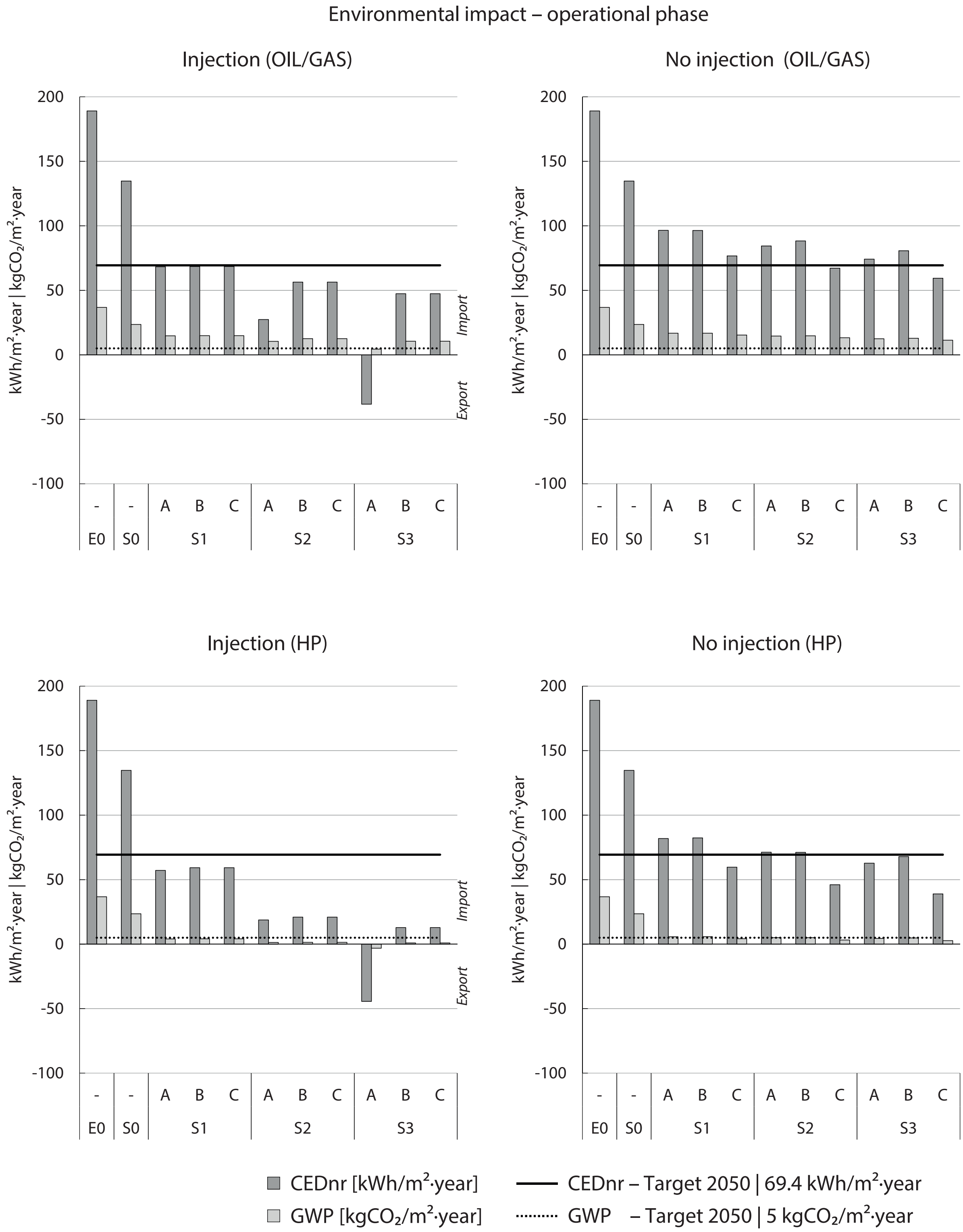


Figure 7-53. Final energy balance, non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP) for the operational phase of the Archetype 4, for each renovation scenario and energy-use scenario (A-100%, B-Selection and C-Batteries), with or without replacing the existing HVAC system and considering or not the possibility to inject into the grid.

Results for all indicators of this group are presented in Table 7-25.

Operational phase		OIL/GAS			HP	
E0 - Current Status						
Consumption [kWh/m^2·year]						
Oil		110				
Electricity		19				
CED$_{nr}$ [kWh$_{NRE}$/m^2·year]		182			-	
GWP [kgCO_2/m^2·year]		35				
HVAC Power needed [kW]		460				
S0 - Baseline						
Consumption [kWh/m^2·year]						
Oil		65				
Electricity		19				
CED$_{nr}$ [kWh$_{NRE}$/m^2·year]		128			-	
GWP [kgCO_2/m^2·year]		22				
HVAC Power needed [kW]		194				
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Oil		47			-	
Electricity		19			34	
PVSC [kWh$_{e\text{-}pv}$/m^2·year]	5	5	12	6	6	14
PVI [kWh$_{e\text{-}pv}$/m^2·year]	10	10	3	9	8	0
SS | SC [%]	32 | 35	32 | 35	73 | 81	21 | 43	21 | 44	42 | 99
CED$_{nr}$ [kWh$_{NRE}$/m^2·year]	68	68	68	57	59	59
GWP [kgCO_2/m^2·year]	15	15	15	4	4	4
HVAC Power needed [kW]			131			
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Oil		40			-	
Electricity		19			32	
PVSC [kWh$_{e\text{-}pv}$/m^2·year]	7	5	12	8	8	17
PVI [kWh$_{e\text{-}pv}$/m^2·year]	20	11	4	18	17	9
SS | SC [%]	40 | 25	32 | 32	79 | 77	30 | 31	29 | 32	62 | 66
CED$_{nr}$ [kWh$_{NRE}$/m^2·year]	27	56	56	19	21	21
GWP [kgCO_2/m^2·year]	10	13	13	1	1	1
HVAC Power needed [kW]			116			
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Oil		34			-	
Electricity		19			30	
PVSC [kWh$_{e\text{-}pv}$/m^2·year]	7	5	12	9	7	17
PVI [kWh$_{e\text{-}pv}$/m^2·year]	39	11	4	37	19	9
SS | SC [%]	45 | 16	32 | 31	80 | 75	36 | 20	29 | 28	71 | 66
CED$_{nr}$ [kWh$_{NRE}$/m^2·year]	-38	47	47	-44	13	13
GWP [kgCO_2/m^2·year]	4	11	11	-3	1	1
HVAC Power needed [kW]			103			

Table 7-25. Final energy balance (operational phase) indicator values obtained for the different scenarios and variants for Archetype 4, taking into account the injection of the electricity overproduction into the grid. Negative values correspond to positive energy scenarios (the energy produced is higher than the consumption).

Life-Cycle Assessment (LCA)

The global LCA results for Archetype 4 are graphically shown in Figure 7-54 and Figure 7-55. Considering the injection of the electricity overproduced (Figure 7-54), if the oil-boiler is maintained, none of the scenarios respect both limits (CEDnr and GWP). However, when the oil-boiler is replaced by a HP, the three BIPV scenarios comply with the requirements of the 2'000-Watt Society (310 $MJ/m^2\cdot year$ and 10 $kgCO_2/m^2\cdot year$). If the injection into the grid is not available (Figure 7-55), only BIPV scenarios (S1 to S3 replacing the oil-boiler) achieve both targets.

In terms of payback times shown in Table 7-26, values obtained are between 3.1-5.4 years (for EPBT) and 3.7-8.5 years (for GPBT) if the injection into the grid is possible, and slightly higher, between 4.1-7.2 years (for EPBT) and 3.9-9.9 years (for GPBT) without injection.

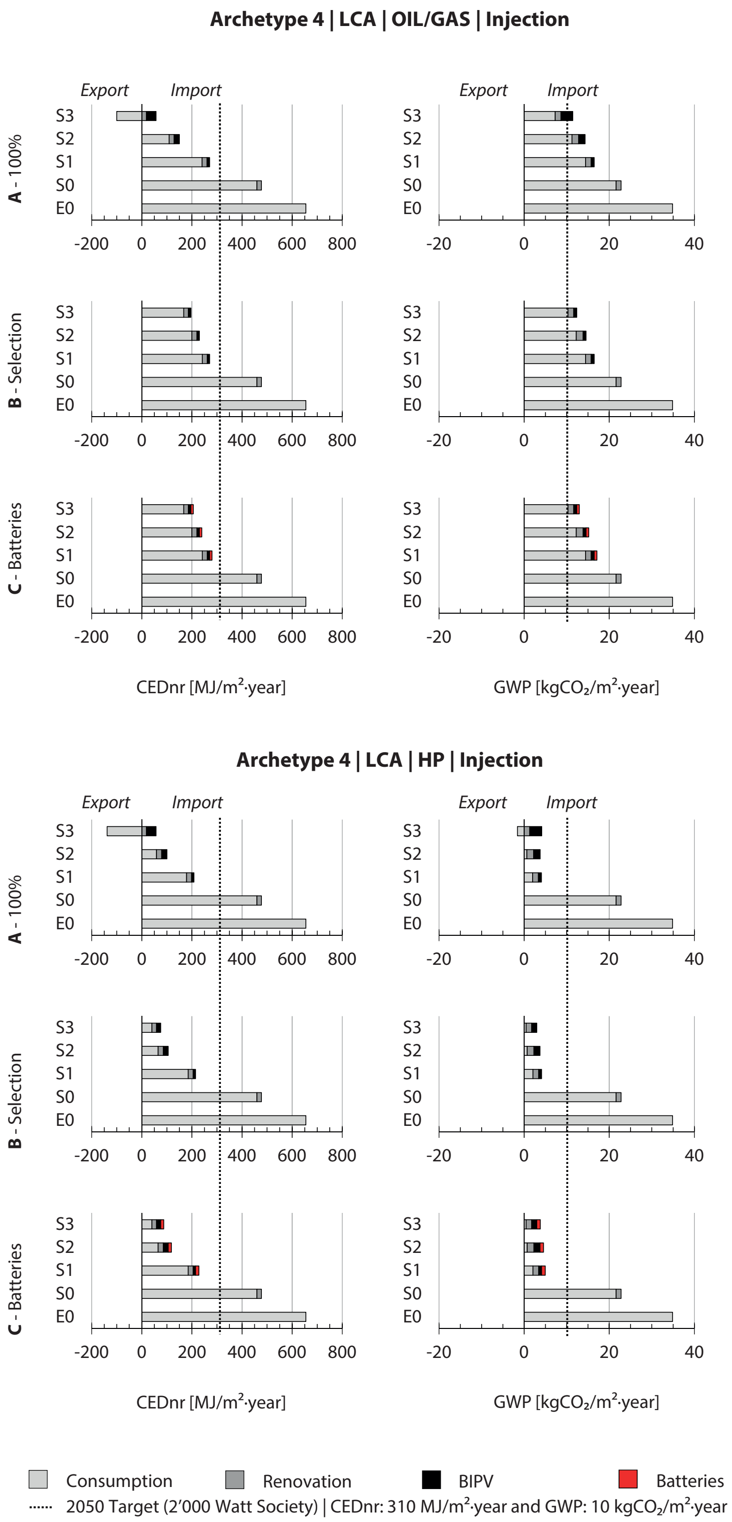
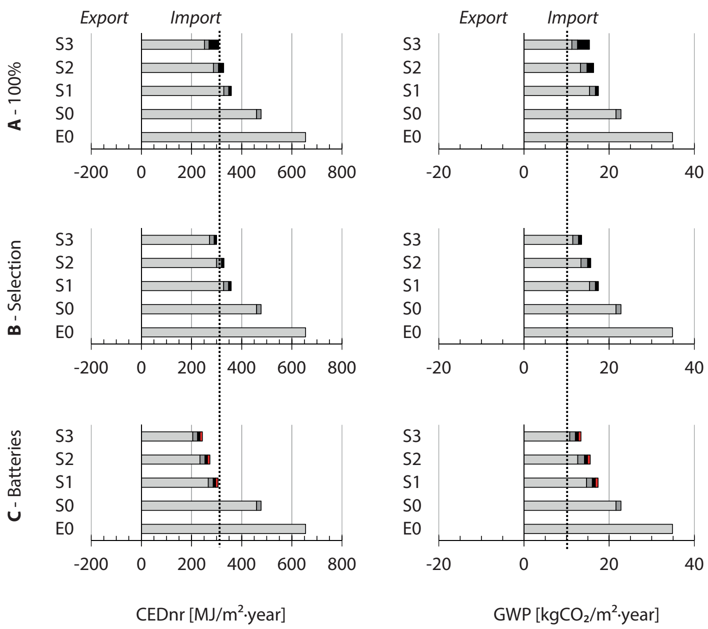


Figure 7-54. LCA results for Archetype 4 (injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

Archetype 4 | LCA | OIL/GAS | No injection



Archetype 4 | LCA | HP | No injection

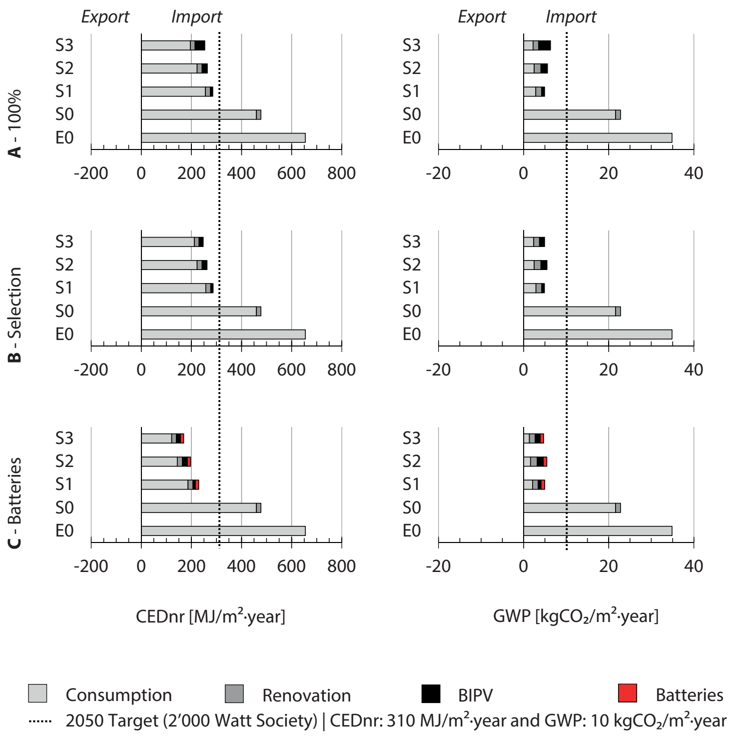


Figure 7-55. LCA results for Archetype 4 (self-consumption approach without injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

LCA	OIL/GAS			HP		
E0 – Current Status	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	655	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	35	-	-	-	-	-
EPBT [years]	-	-	-	-	-	-
GPBT [years]	-	-	-	-	-	-
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	477	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	23	-	-	-	-	-
EPBT [years]	5.5	-	-	-	-	-
GPBT [years]	5.3	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	268	269	278	207	213	226
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	16	16	17	4	4	5
EPBT [years]	4.0	4.0	5.4	3.6	3.6	5.3
GPBT [years]	5.9	5.9	7.7	3.8	3.7	5.3
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	145	228	237	96	102	115
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	14	14	15	4	4	4
EPBT [years]	4.0	3.7	4.9	3.8	3.7	5.0
GPBT [years]	7.5	5.9	7.5	5.3	5.2	6.6
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	-52	194	203	-89	72	85
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	11	12	13	2	3	4
EPBT [years]	3.8	3.2	4.4	3.7	3.1	4.4
GPBT [years]	8.5	4.9	6.3	6.5	4.3	5.8
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	356	356	304	284	285	228
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	17	17	17	5	5	5
EPBT [years]	5.0	5.0	5.7	4.3	4.2	5.3
GPBT [years]	6.2	6.2	7.8	3.9	3.8	5.3
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	323	327	271	260	259	193
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	16	16	15	6	5	5
EPBT [years]	6.0	4.7	5.3	5.2	5.1	5.8
GPBT [years]	8.2	6.2	7.7	5.6	5.5	6.8
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	299	298	241	245	244	166
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	15	13	13	6	5	5
EPBT [years]	7.2	4.1	4.7	6.4	4.4	5.0
GPBT [years]	9.9	5.1	6.4	7.3	4.6	5.9

Table 7-26. LCA indicator values obtained for the different scenarios and variants for Archetype 4, with and without injection possibility. Values in bold respect the 2050 targets (2’000-Watt Society).

Life-cycle cost (LCC)

From the cumulative energy consumption costs curves of Figure 7-56, we observe that this archetype presents the best results compared to the other archetypes. Compared to the 28 years SPBT of S0, the SPBT of BIPV scenarios are much lower, reaching almost half that value at just over 15 years for S1 and S2 (with HP).

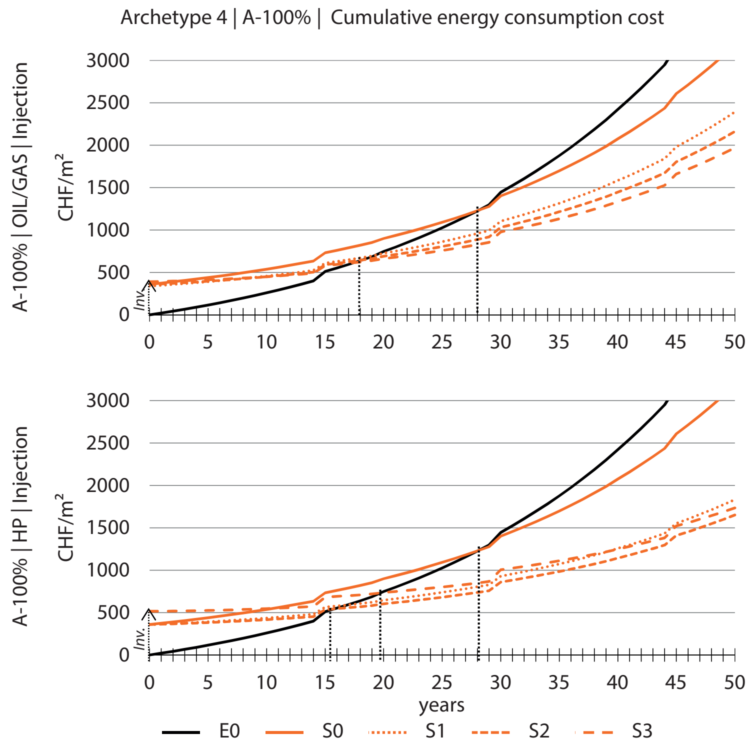


Figure 7-56. Cumulative energy consumption cost for Archetype 4, considering A-100%, OIL/GAS, HP and Injection.

The IRR for S0 (Figure 7-57) is of only 0.9%. This value makes it almost impossible to convince the owner to invest in this kind of renovation. However, the IRR of all BIPV scenarios is higher and achieves up to 6.6% for scenario S3 (when replacing the oil-boiler and including batteries).

Among the BIPV scenarios, the slightly lower values for the S3 scenarios with HP, between 4.1-4.6%, are still considerably good and may be sufficient to convince the owner to give up a little profitability compared to scenario S2 (with IRR of 6.6%) in order to achieve the best possible performance (in terms of energy, environmental impact and interior comfort).

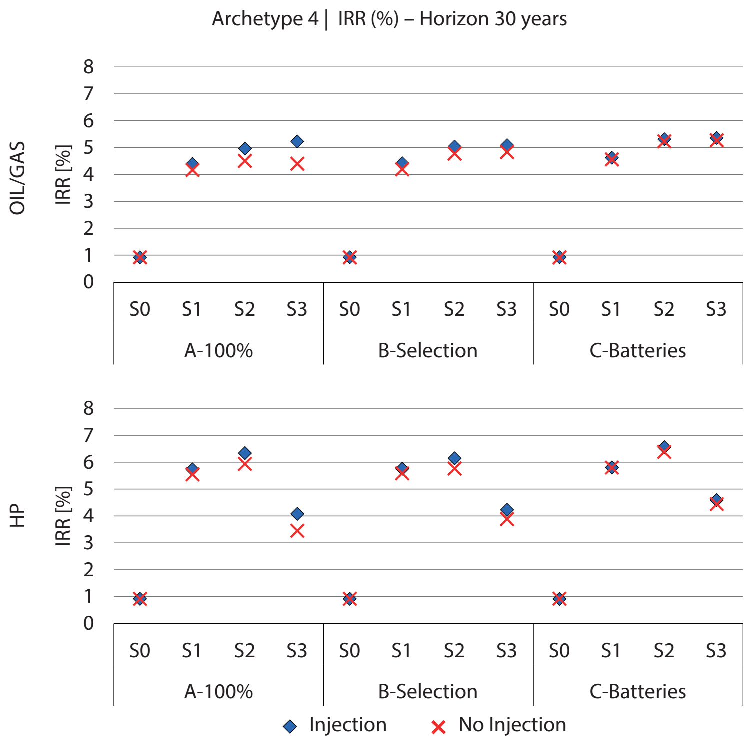


Figure 7-57. Internal rate of return (IRR) for Archetype 4 with a 30-year horizon of each renovation scenario, taking into account the different energy-use scenarios (A, B, and C).

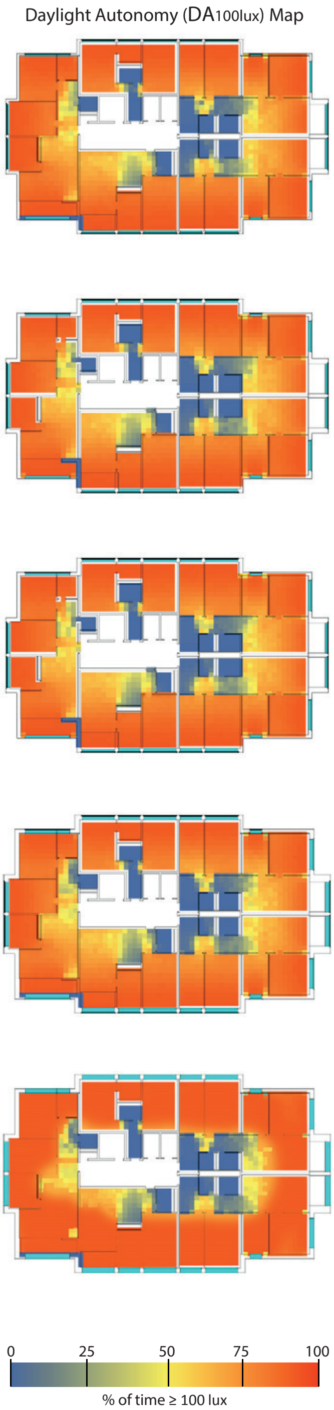
Results for all economic indicators for Archetype 4 are presented in Table 7-27.

LCC	OIL/GAS			HP		
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m2]	360	-	-	-	-	-
NPV* [CHF/m2]	-107	-	-	-	-	-
IRR* [%]	0.9	-	-	-	-	-
DPBT [years]	41	-	-	-	-	-
SPBT [years]	28	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	338	337	365	357	354	388
NPV* [CHF/m2]	81	82	104	179	180	202
IRR* [%]	4.4	4.4	4.6	5.7	5.8	5.8
DPBT [years]	25	25	24	21	21	21
SPBT [years]	19	19	19	16	16	16
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	357	337	361	359	367	384
NPV* [CHF/m2]	121	122	151	223	213	260
IRR* [%]	5.0	5.0	5.3	6.3	6.1	6.6
DPBT [years]	23	23	22	19	20	19
SPBT [years]	18	18	17	15	16	15
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	391	358	381	516	477	508
NPV* [CHF/m2]	148	133	163	89	97	139
IRR* [%]	5.2	5.1	5.4	4.1	4.2	4.6
DPBT [years]	22	23	22	26	25	24
SPBT [years]	17	18	17	19	19	19
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	338	337	365	357	354	388
NPV* [CHF/m2]	68	69	100	168	169	202
IRR* [%]	4.2	4.2	4.6	5.5	5.6	5.8
DPBT [years]	26	26	25	22	22	21
SPBT [years]	19	19	19	17	17	16
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	357	337	361	359	367	384
NPV* [CHF/m2]	94	107	146	198	189	248
IRR* [%]	4.5	4.8	5.2	5.9	5.8	6.4
DPBT [years]	25	24	23	21	21	20
SPBT [years]	19	18	17	16	16	16
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	391	358	381	516	477	508
NPV* [CHF/m2]	94	117	157	38	71	126
IRR* [%]	4.4	4.8	5.3	3.4	3.9	4.4
DPBT [years]	25	24	22	28	27	25
SPBT [years]	19	18	17	21	20	19

Table 7-27. LCC indicator values obtained for the different scenarios and variants for Archetype 4, with and without injection possibility. * Horizon of 30 years for NPV and IRR calculations.

Indoor comfort

Results shown in Figure 7-58 indicate that, despite a rise in the number of hours with an indoor temperature above 26.5°C, the overheating limit of 100 hours/year is respected for all scenarios. The sDA remains almost constant (around 82%) for E0 to S2 and achieves 92% in S3 due to the increase in the windows size.



E0 – Current Status

Overheating
OH: 14 hours/year*

Daylighting
$sDA_{100lux,\ 50\%}$: 82% of floor area
DF: 3.9%

S0 – Baseline

Overheating
OH: 74 hours/year*

Daylighting
$sDA_{100lux,\ 50\%}$: 82% of floor area
DF: 3.7%

S1 – BIPV Conservation

Overheating
OH: 80 hours/year*

Daylighting
$sDA_{100lux,\ 50\%}$: 82% of floor area
DF: 3.7%

S2 – BIPV Renovation

Overheating
OH: 64 hours/year*

Daylighting
$sDA_{100lux,\ 50\%}$: 81% of floor area
DF: 3.2%

S3 – BIPV Transformation

Overheating
OH: 74 hours/year*

Daylighting
$sDA_{100lux,\ 50\%}$: 92% of floor area
DF: 4.3%

OH*: Overheating hours at Ti>26.5°C*
sDA*: Spatial Daylight Autonomy*
DF*: Mean Daylight Factor*

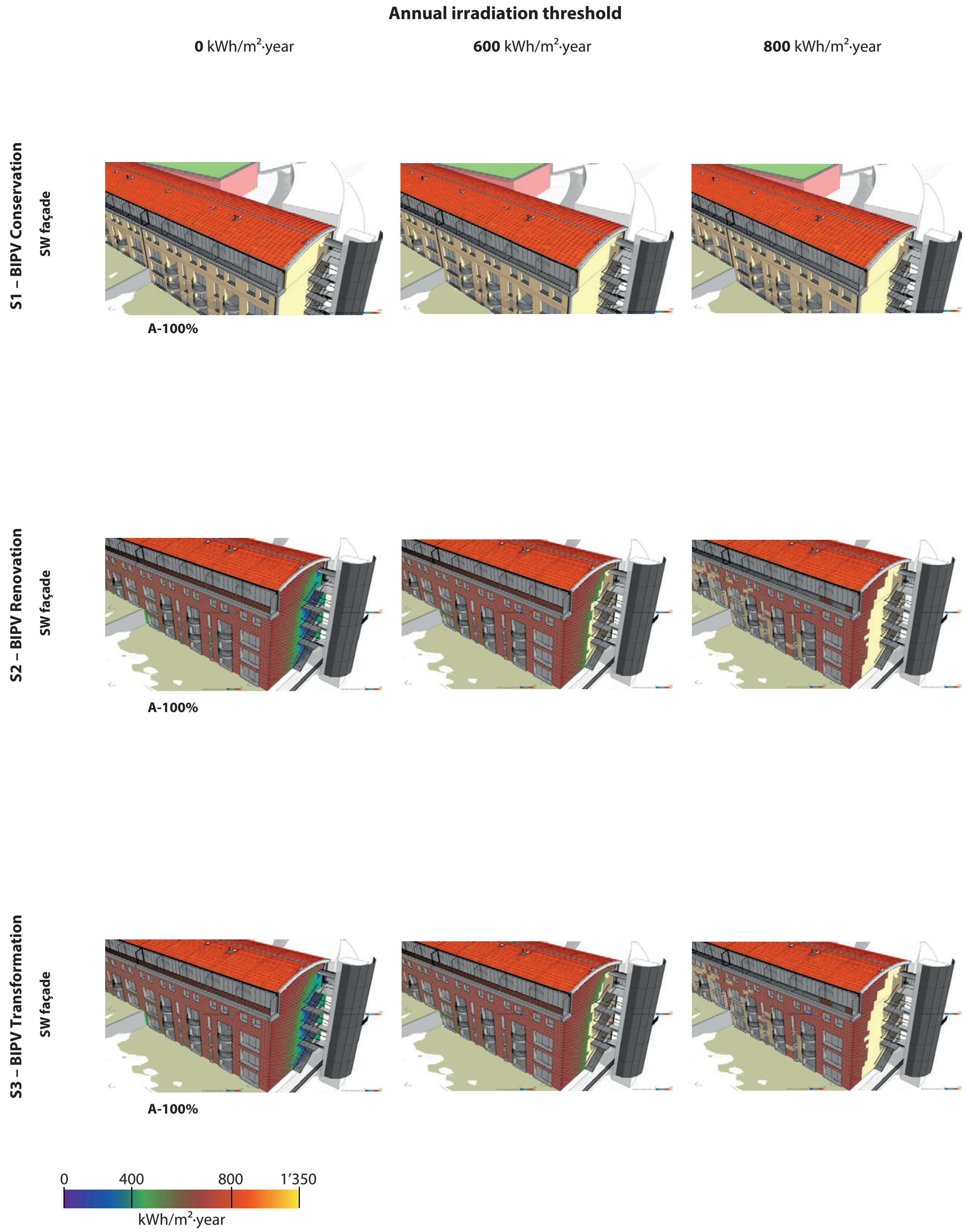
** Requirements SIA 180 standard: limit to 100h/year at T>26.5°C*

Figure 7-58. Results of the overheating and daylighting study for Archetype 4.

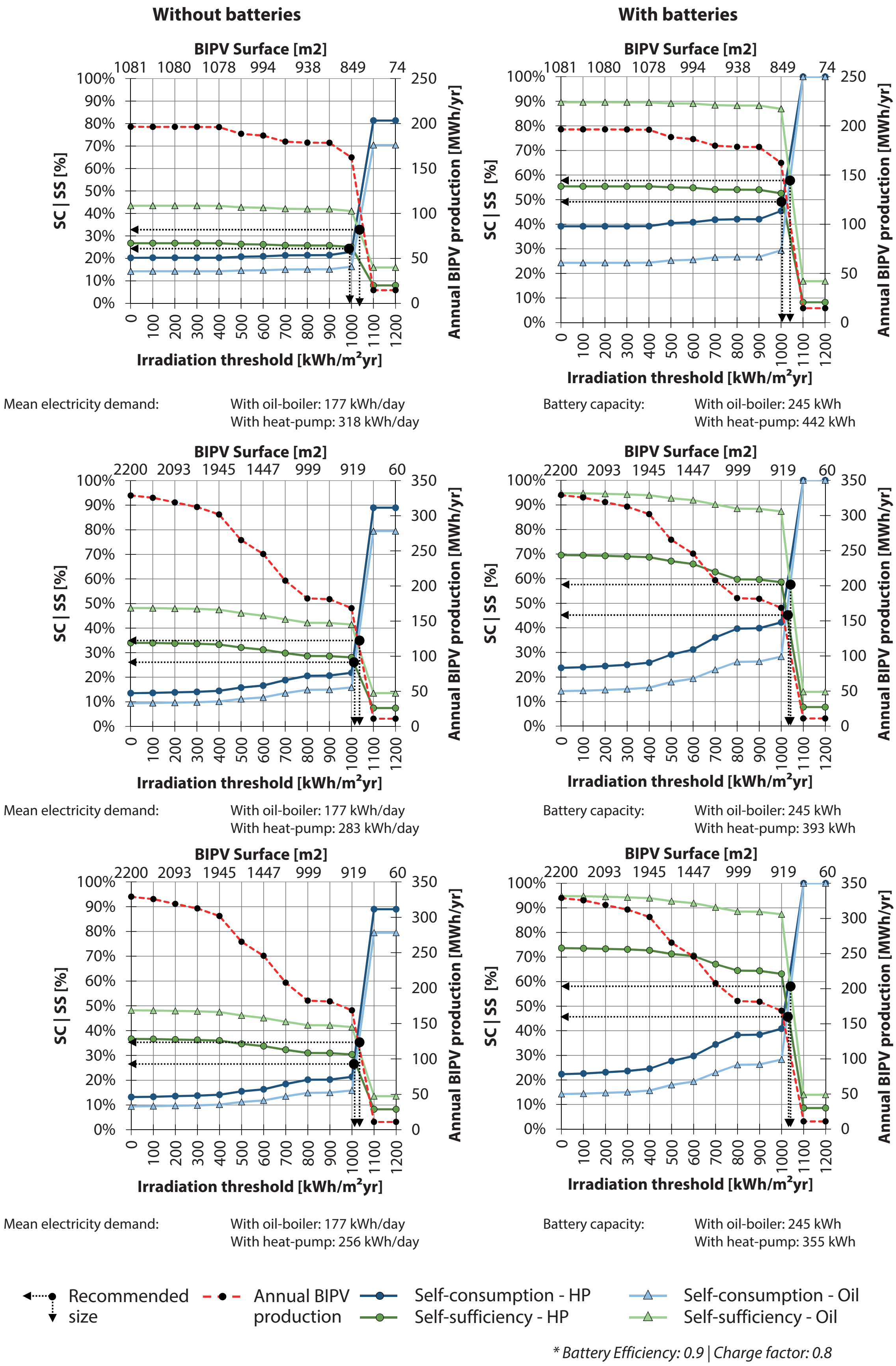
7.3.5. Archetype 5

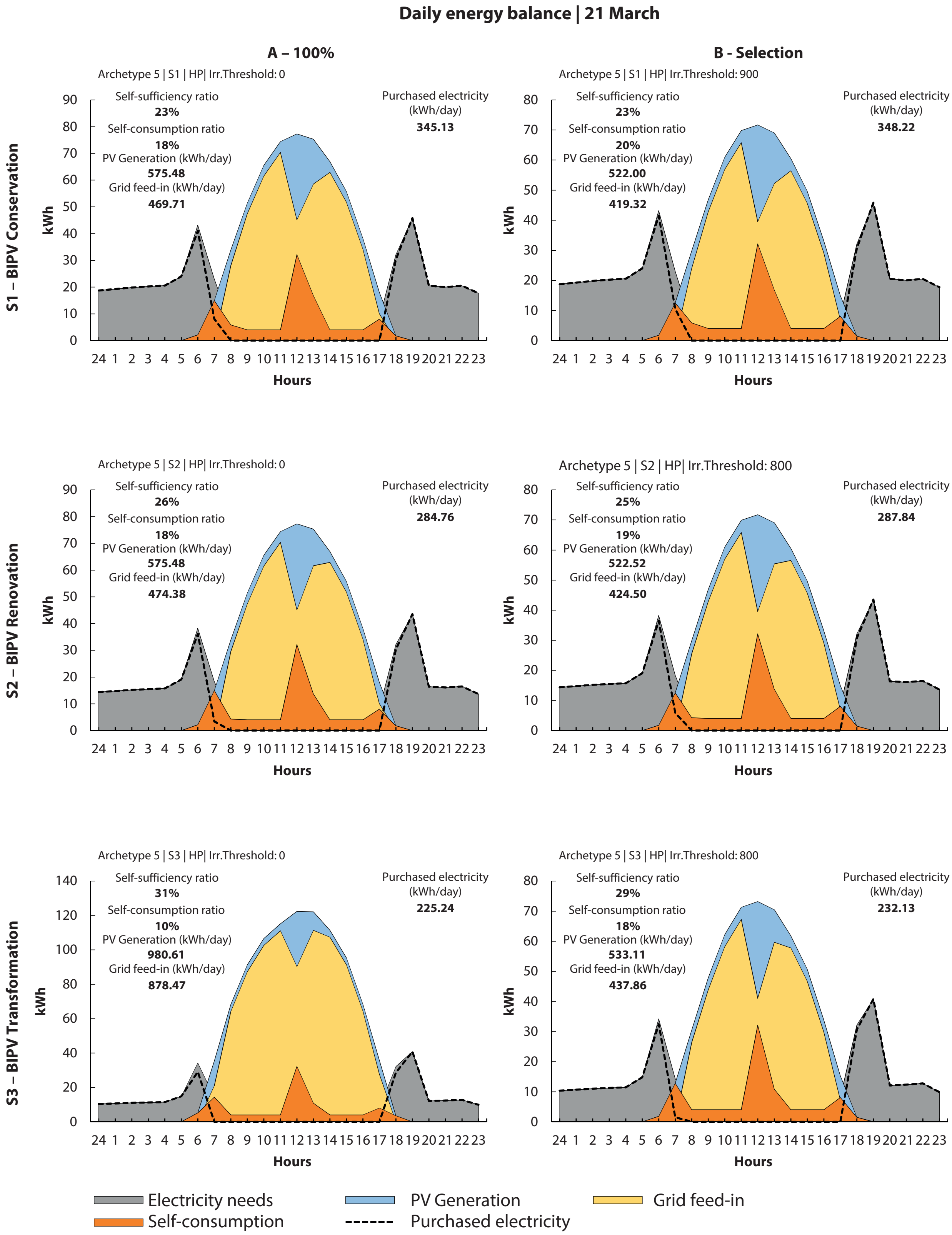
Sizing of BIPV installation

Figure 7-59 presents the results of the active surfaces selection for Archetype 5. For this archetype, mainly due to the large curved roof, the best equilibrium between SS and SC is achieved at 1’000-1’100 kWh/m^2·year, both when maintaining and replacing the gas-boiler. For scenario S1 (with only roof and attic balconies considered), the SS-SC curves remain almost parallel between 0 to 1’000 kWh/m^2·year due to the dominance of the roof surfaces. We can also notice that the PV production is practically the same over this range, followed by a rapid decrease.



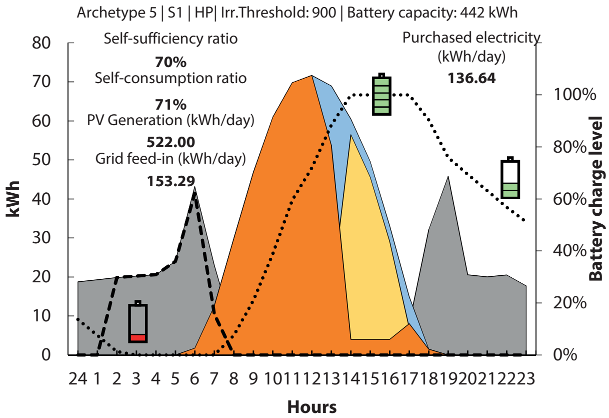
Annual irradiation threshold
0 kWh/m²·year
600 kWh/m²·year
800 kWh/m²·year
S1 – BIPV Conservation
SW façade
A-100%
S2 – BIPV Renovation
SW façade
A-100%
S3 – BIPV Transformation
SW façade
A-100%
0
400
800
1'350
kWh/m²·year

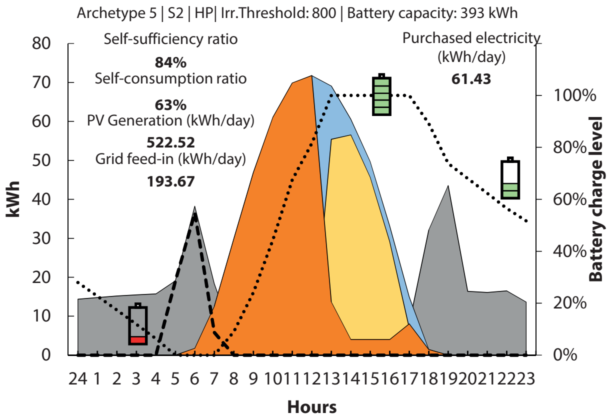

Without batteries
With batteries
BIPV Surface [m2]
1081 1080 1078 994 938 849 74
2200 2093 1945 1447 999 919 60
SC | SS [%]
Annual BIPV production [MWh/yr]
Irradiation threshold [kWh/m²yr]
Mean electricity demand:
With oil-boiler: 177 kWh/day
With heat-pump: 318 kWh/day
Battery capacity:
With oil-boiler: 245 kWh
With heat-pump: 442 kWh
Mean electricity demand:
With oil-boiler: 177 kWh/day
With heat-pump: 283 kWh/day
Battery capacity:
With oil-boiler: 245 kWh
With heat-pump: 393 kWh
Mean electricity demand:
With oil-boiler: 177 kWh/day
With heat-pump: 256 kWh/day
Battery capacity:
With oil-boiler: 245 kWh
With heat-pump: 355 kWh
Recommended size
Annual BIPV production
Self-consumption - HP
Self-sufficiency - HP
Self-consumption - Oil
Self-sufficiency - Oil
* Battery Efficiency: 0.9 | Charge factor: 0.8

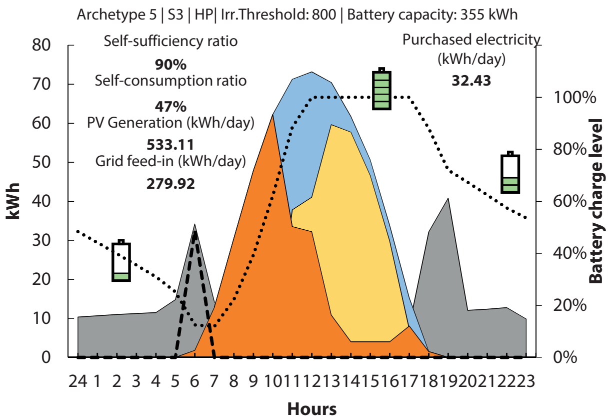


Daily energy balance | 21 March
A – 100%
B - Selection
S1 – BIPV Conservation
S2 – BIPV Renovation
S3 – BIPV Transformation
Archetype 5 | S1 | HP| Irr.Threshold: 0
Self-sufficiency ratio 23%
Self-consumption ratio 18%
PV Generation (kWh/day) 575.48
Grid feed-in (kWh/day) 469.71
Purchased electricity (kWh/day) 345.13
Archetype 5 | S1 | HP| Irr.Threshold: 900
Self-sufficiency ratio 23%
Self-consumption ratio 20%
PV Generation (kWh/day) 522.00
Grid feed-in (kWh/day) 419.32
Purchased electricity (kWh/day) 348.22
Archetype 5 | S2 | HP| Irr.Threshold: 0
Self-sufficiency ratio 26%
Self-consumption ratio 18%
PV Generation (kWh/day) 575.48
Grid feed-in (kWh/day) 474.38
Purchased electricity (kWh/day) 284.76
Archetype 5 | S2 | HP| Irr.Threshold: 800
Self-sufficiency ratio 25%
Self-consumption ratio 19%
PV Generation (kWh/day) 522.52
Grid feed-in (kWh/day) 424.50
Purchased electricity (kWh/day) 287.84
Archetype 5 | S3 | HP| Irr.Threshold: 0
Self-sufficiency ratio 31%
Self-consumption ratio 10%
PV Generation (kWh/day) 980.61
Grid feed-in (kWh/day) 878.47
Purchased electricity (kWh/day) 225.24
Archetype 5 | S3 | HP| Irr.Threshold: 800
Self-sufficiency ratio 29%
Self-consumption ratio 18%
PV Generation (kWh/day) 533.11
Grid feed-in (kWh/day) 437.86
Purchased electricity (kWh/day) 232.13
kWh
Hours
24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Electricity needs
Self-consumption
PV Generation
Purchased electricity
Grid feed-in

C - Batteries







For the example daily energy balance shown in Figure 7-60, results present similar values to the previous archetypes, achieving a SS between 23% and 90% and a SC ranging from 10% to 71% (for the scenarios with batteries).

Table 7-28 presents the final values defining all variants for Archetype 5.

The irradiation threshold values have been fixed at 1’000 kWh/m², for all B and C scenarios, although the best equilibrium between SS and SC appears to be somewhere along the production drop that occurs between 1’000 and 1’100 kWh/m²·year. A more detailed study would be required within that range to precisely identify the best SC-SS trade-off position.

Given that choice of threshold, for scenarios where the gas-boiler is kept, the values of SS and SC do not reflect a very good equilibrium. However, they are closer for the HP cases, particularly for the B-Selection scenario where both values are between 21-30%.

Active surfaces selection		**OIL/GAS**			**HP**	
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	1000	1000	0	1000	1000
SS [%]	43%	41%	87%	27%	25%	53%
SC [%]	14%	16%	29%	20%	23%	45%
Annual production [MWh]	179	162	162	179	162	162
BIPV surfaces [m²]	941	849	849	941	849	849
BIPV installation size [kWp] STC	161	146	146	161	146	162
Battery size [kWh]	-	-	367	-	-	663
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	1000	1000	0	1000	1000
SS [%]	48%	41%	87%	34%	28%	59%
SC [%]	9%	16%	28%	14%	22%	42%
Annual production [MWh]	329	168	168	329	168	168
BIPV surfaces [m²]	2200	919	919	2200	919	919
BIPV installation size [kWp] STC	377	158	158	377	158	158
Battery size [kWh]	-		367	-	-	590
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Irr. Threshold [kWh/m²·year]	0	1000	1000	0	1000	1000
SS [%]	48%	41%	87%	34%	30%	63%
SC [%]	9%	16%	28%	14%	21%	41%
Annual production [MWh]	329	168	168	329	168	168
BIPV surfaces [m²]	2200	919	919	2200	919	919
BIPV installation size [kWp] STC	377	158	158	377	158	158
Battery size [kWh]	-	-	367	-	-	532

Table 7-28. Values defining different BIPV scenarios and variants for Archetype 5.

Photovoltaic performance

Table 7-29 presents the results of the different indicators regarding the photovoltaic performance for each scenario of Archetype 5. In terms of energy (EPBT) and GHG emission (GPBT) payback time, all values are lower than 25 years (performance warranty period of the PV modules) and the carbon content is lower than the grid.

PV performance	OIL/GAS			HP		
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.029	0.029	0.054	0.029	0.029	0.075
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.135	0.135	0.233	0.135	0.135	0.313
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.035	0.035	0.058	0.035	0.035	0.077
$EPBT_{PV}$ [years]	2.8	2.8	4.8	2.8	2.8	6.5
$GPBT_{PV}$ [years]	10.2	10.2	16.9	10.2	10.2	22.3
Energy yield [kWh_{e-pv}/kWh_p]	1112	1111		1112	1111	
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.062	0.055	0.080	0.062	0.055	0.096
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.172	0.141	0.237	0.172	0.141	0.296
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.045	0.037	0.059	0.045	0.037	0.073
$EPBT_{PV}$ [years]	3.5	2.9	4.9	3.5	2.9	6.1
$GPBT_{PV}$ [years]	13.1	10.7	17.2	13.1	10.7	21.2
Energy yield [kWh_{e-pv}/kWh_p]	872	1065		872	1065	
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
$LCOE_{PV}$ [CHF/kWh_{e-pv}]	0.062	0.055	0.080	0.062	0.055	0.092
NRE_{PV} [kWh_{NRE}/ kWh_{e-pv}]	0.172	0.141	0.237	0.172	0.141	0.280
CCF_{PV} [$kgCO_2$/ kWh_{e-pv}]	0.045	0.037	0.059	0.045	0.037	0.069
$EPBT_{PV}$ [years]	3.5	2.9	4.9	3.5	2.9	5.8
$GPBT_{PV}$ [years]	13.1	10.7	17.2	13.1	10.7	20.2
Energy yield [kWh_{e-pv}/kWh_p]	872	1065		872	1065	

Table 7-29. PV performance indicator values obtained for the different BIPV scenarios and variants for Archetype 5.

Energy balance (operational phase)

The power required for heating (Figure 7-61) is reduced from 296 kW (for E0) to 194, 131, 116 and 103 kW for S0, S1, S2 and S3 respectively.

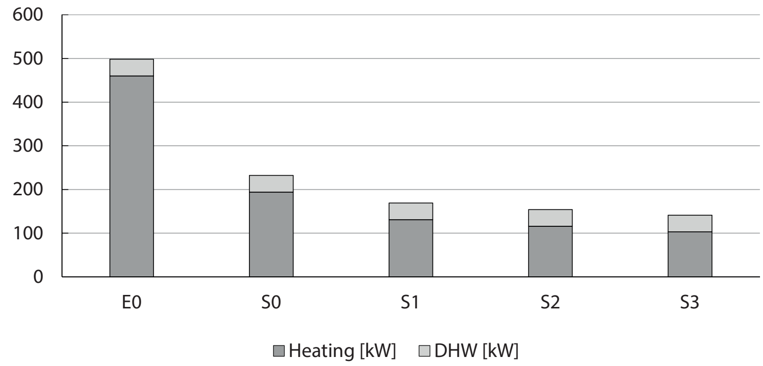
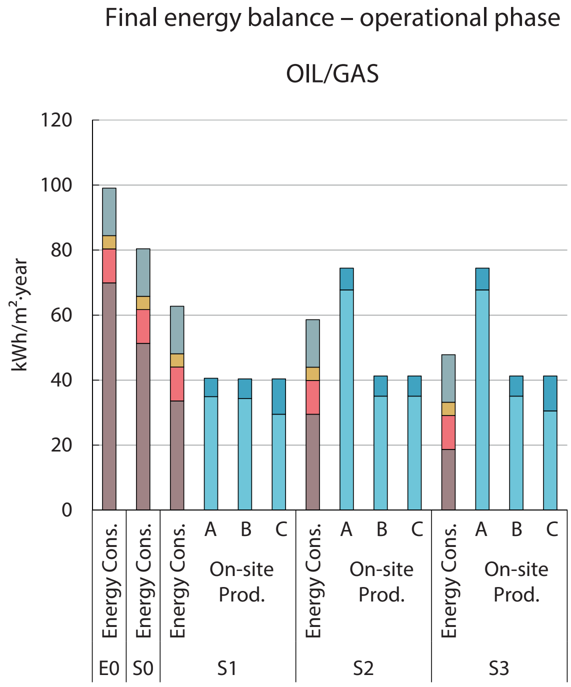
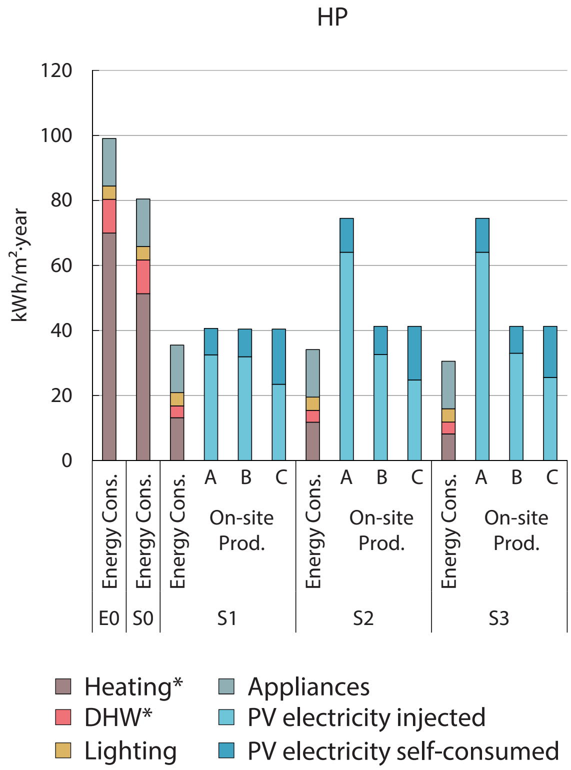


Figure 7-61. Power required for the HVAC system (heating and DHW), Archetype 5.

In terms of final energy balance (Figure 7-62), scenario S0 reaches 19% of energy savings, scenarios S1 to S3 between 36% and 51% when maintaining the existing oil-boiler and 63% (S1), 65% (S2) and 68% (S3) with a HP. Almost all scenarios (with HP) lead to a positive energy building. For this archetype, it is important to highlight that the pre-existence of thermal solar collectors situated vertically on the south façade of the building, covering 50% of the DHW needs, help to achieve these results. Regarding the environmental impact of the energy consumption, all BIPV scenarios replacing the existing gas-boiler by a heat-pump achieve both CEDnr (69.4 kWh/m^2·year) and GWP (5 $kgCO_2/m^2$·year) targets.

Following the same trend than the Archetype 4, in case the injection is not possible, scenarios with batteries help to achieve both targets and if the gas-boiler is replaced, all options of scenario S3 fulfil the objectives.





* Oil / Gas when HVAC is maintained and Electricity if a Heat-Pump is installed.

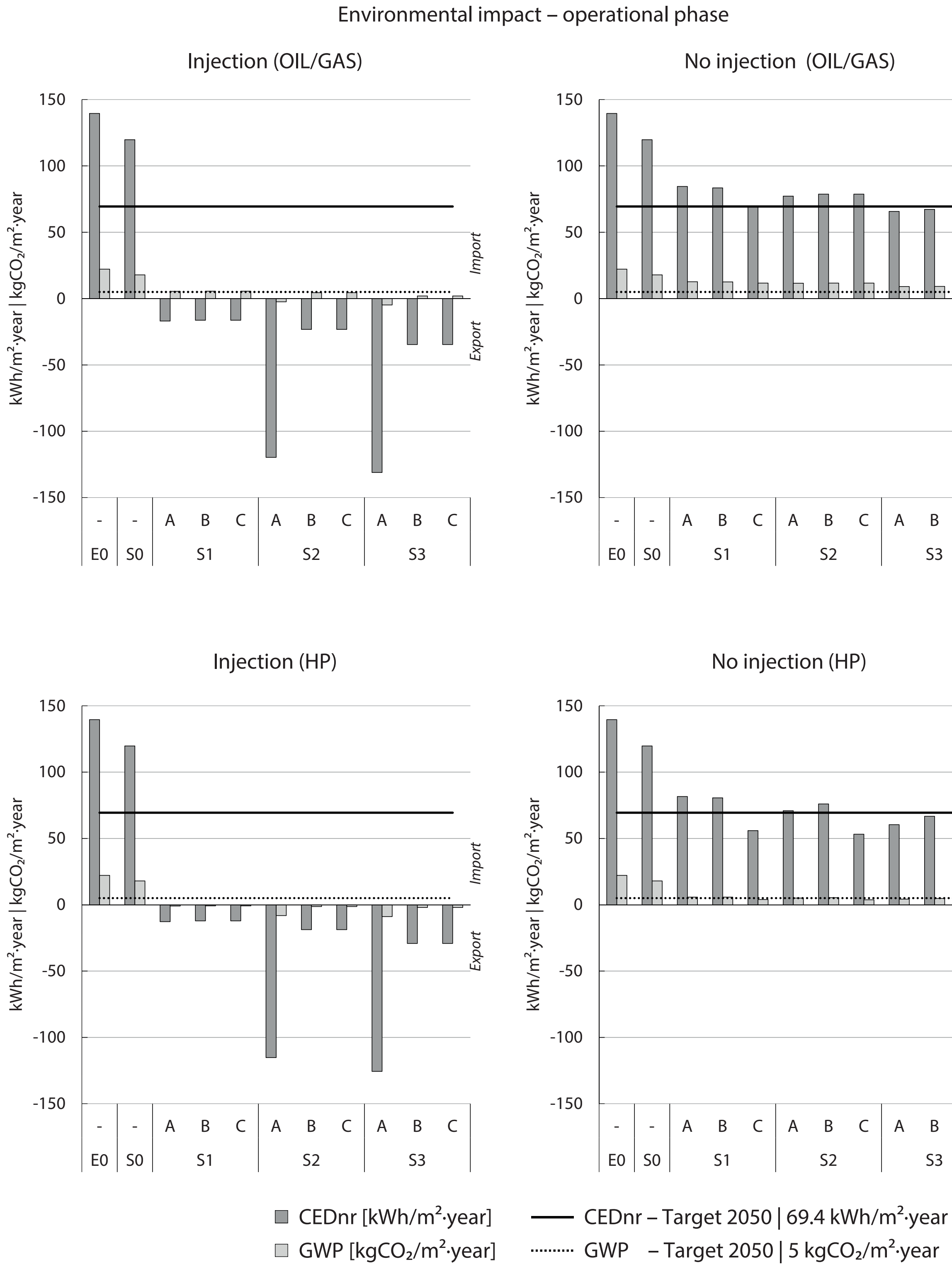


Figure 7-62. Final energy balance, non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP) for the operational phase of the Archetype 5, for each renovation scenario and energy-use scenario (A-100%, B-Selection and C-Batteries), with or without replacing the existing HVAC system and considering or not the possibility to inject into the grid.

Results for all indicators of this group are presented in Table 7-30.

Operational phase		OIL/GAS			HP	
E0 - Current Status						
Consumption [kWh/m^2·year]						
Gas		80				
Electricity		19				
CED_{nr} [kWh_{NRE}/m^2·year]		132			-	
GWP [$kgCO_2$/m^2·year]		20				
HVAC Power needed [kW]		296				
S0 - Baseline						
Consumption [kWh/m^2·year]						
Gas		62				
Electricity		19				
CED_{nr} [kWh_{NRE}/m^2·year]		113			-	
GWP [$kgCO_2$/m^2·year]		16				
HVAC Power needed [kW]		194				
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Gas		44				
Electricity		19				
PVSC [kWh_{e-pv}/m^2·year]	6	6	11	8	8	17
PVI [kWh_{e-pv}/m^2·year]	35	34	30	32	32	23
SS | SC [%]	43 | 14	42 | 15	88 | 27	27 | 20	26 | 21	54 | 42
CED_{nr} [kWh_{NRE}/m^2·year]	-17	-16	-16	-13	-12	-12
GWP [$kgCO_2$/m^2·year]	6	6	6	-1	-1	-1
HVAC Power needed [kW]			131			
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Gas		40				
Electricity		19				
PVSC [kWh_{e-pv}/m^2·year]	7	6	6	10	9	17
PVI [kWh_{e-pv}/m^2·year]	68	35	35	64	33	25
SS | SC [%]	48 | 9	42 | 15	42 | 15	34 | 14	29 | 21	60 | 40
CED_{nr} [kWh_{NRE}/m^2·year]	-120	-23	-23	-115	-19	-19
GWP [$kgCO_2$/m^2·year]	-2	4	4	-8	-1	-1
HVAC Power needed [kW]			116			
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Consumption [kWh/m^2·year]						
Gas		29				
Electricity		19				
PVSC [kWh_{e-pv}/m^2·year]	7	6	11	10	8	16
PVI [kWh_{e-pv}/m^2·year]	68	35	31	64	33	26
SS | SC [%]	48 | 9	42 | 15	89 | 26	34 | 14	31 | 20	64 | 38
CED_{nr} [kWh_{NRE}/m^2·year]	-131	-35	-35	-126	-29	-29
GWP [$kgCO_2$/m^2·year]	-5	2	2	-9	-2	-2
HVAC Power needed [kW]			103			

Table 7-30. Final energy balance (operational phase) indicator values obtained for the different scenarios and variants for Archetype 5, taking into account the injection of the electricity overproduction into the grid. Negative values correspond to positive energy scenarios (the energy produced is higher than the consumption).

Life-Cycle Assessment (LCA)

Regarding the global LCA results, when injecting the electricity overproduced (Figure 7-63), all BIPV scenarios meet the CEDnr and GWP targets independently of the HVAC system (mainly because the existing one is already efficient), except the S1 with batteries. If the injection into the grid is not available (Figure 7-64), only BIPV scenarios replacing the gas-boiler and using batteries achieve both targets.

In terms of payback times (Table 7-31), values obtained are between 3.2-6.6 years (for EPBT) and 6.8-15.6 years (for GPBT) if the injection into the grid is possible, and slightly higher, between 6.9-13.5 years (for EPBT) and 8.1-25.2 years (for GPBT) without injection.

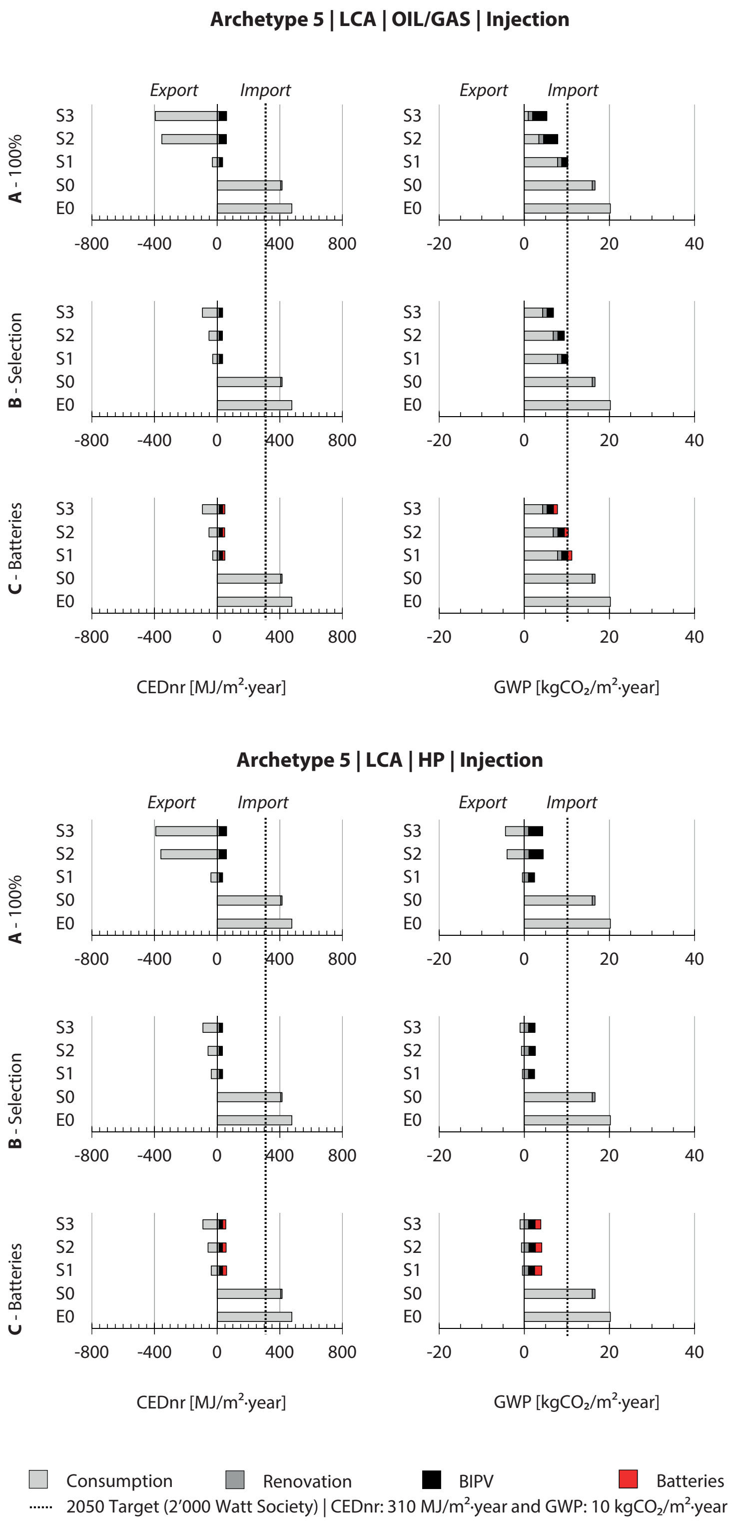


Figure 7-63. LCA results for Archetype 5 (injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

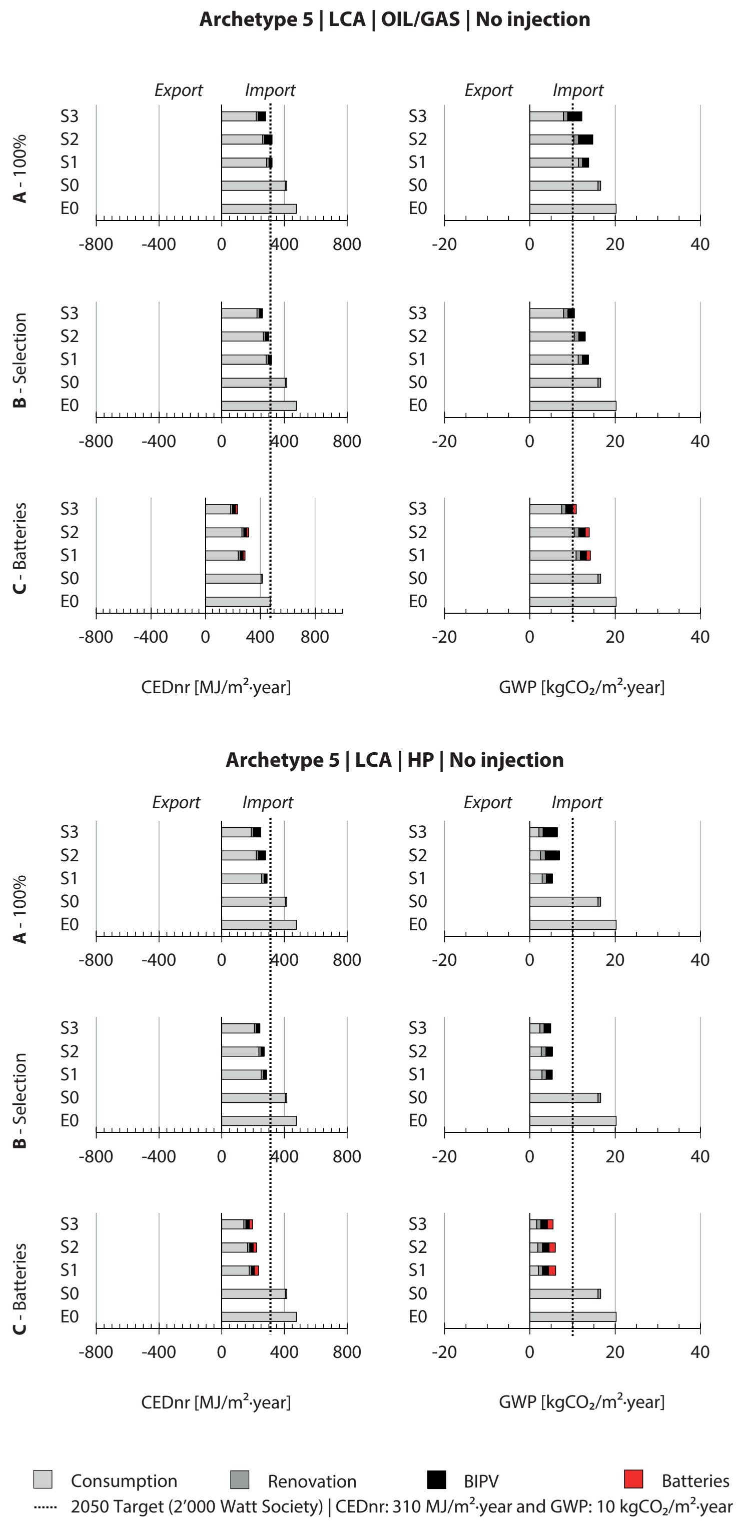


Figure 7-64. LCA results for Archetype 5 (self-consumption approach without injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

LCA	OIL/GAS			HP		
E0 – Current Status	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	476	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	20	-	-	-	-	-
EPBT [years]	-	-	-	-	-	-
GPBT [years]	-	-	-	-	-	-
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	415	-	-	-	-	-
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	17	-	-	-	-	-
EPBT [years]	7.9	-	-	-	-	-
GPBT [years]	8.6	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	-1	1	15	-9	-7	19
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	10	10	11	2	2	4
EPBT [years]	3.6	3.6	5.3	3.6	3.6	6.6
GPBT [years]	11.1	11.1	15.6	6.8	6.8	11.7
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	-305	-23	-9	-310	-28	-5
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	8	9	10	0	2	3
EPBT [years]	3.5	3.3	4.9	3.5	3.4	5.9
GPBT [years]	14.9	11.1	15.3	10.4	7.3	11.6
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	-346	-64	-49	-342	-60	-40
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	5	7	8	0	1	3
EPBT [years]	3.4	3.2	4.7	3.5	3.2	5.4
GPBT [years]	12.7	9.0	12.5	10.0	6.9	10.7
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	316	313	283	286	282	231
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	14	14	14	5	5	6
EPBT [years]	9.5	9.3	11.2	8.3	8.2	11.2
GPBT [years]	15.6	15.5	20.6	8.1	8.1	13.2
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	310	295	309	271	267	219
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	14	13	14	7	5	6
EPBT [years]	13.5	8.3	12.4	11.6	7.5	10.3
GPBT [years]	25.2	15.2	20.8	14.2	8.7	13.1
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
CEDnr [$MJ_{NRE}/m^2 \cdot year$]	269	255	228	239	239	193
GWP [$kgCO_{2\text{-}eq}/m^2 \cdot year$]	12	10	11	6	5	5
EPBT [years]	11.5	7.1	9.1	10.4	6.9	9.2
GPBT [years]	19.7	11.7	15.6	13.6	8.2	12.2

Table 7-31. LCA indicator values obtained for the different scenarios and variants for Archetype 5, with and without injection possibility. Values in bold respect the 2050 targets (2'000-Watt Society).

Life-cycle cost (LCC)

As seen in Figure 7-65, the SPBT of BIPV scenarios (26 years and below) are much lower than the 43 years of S0.

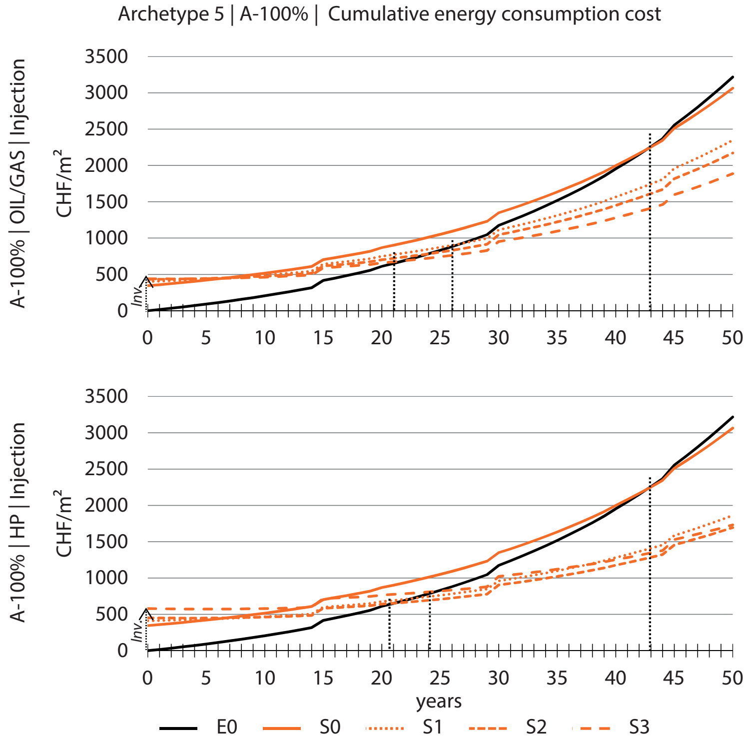


Figure 7-65. Cumulative energy consumption cost for Archetype 5, considering A-100%, OIL/GAS, HP and Injection.

Figure 7-66 indicates that for S0, the internal rate of return is at -3.1%. This value is expected because this archetype is the most recent one (built in 1990), with the best energy performance among all case studies. For this scenario, the energy savings generated from the replacement of the windows, financially expensive, are not sufficient to make the intervention cost-effective.

Although this archetype is only 29 years old, the IRR for all BIPV scenarios are higher, achieving up to 3.2%. The highest value occurs in scenario S2 (A-100%), replacing the gas-boiler. However, as the existing heating system is recent and efficient, this intervention is unlikely. Results for scenarios where the gas-boiler is maintained present a growth pattern from S1 to S3, with the highest values between 2.5% and 2.8%.

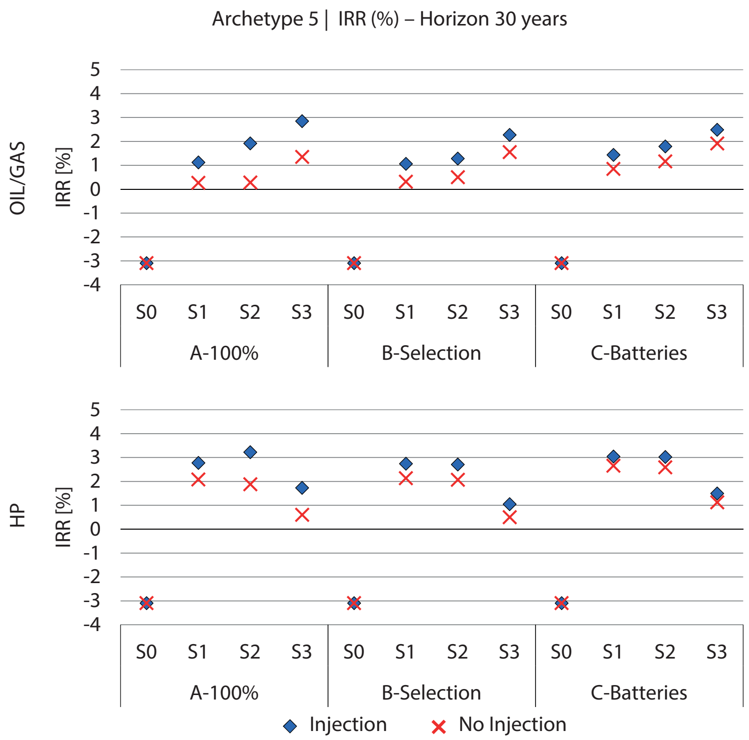


Figure 7-66. Internal rate of return (IRR) for Archetype 5 with a 30-year horizon of each renovation scenario, taking into account the different energy-use scenarios (A, B, and C).

Results for all economic indicators for Archetype 5 are presented in Table 7-32.

LCC	OIL/GAS			HP		
S0 – Baseline	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m2]	345	-	-	-	-	-
NPV* [CHF/m2]	-225	-	-	-	-	-
IRR* [%]	-3.1	-	-	-	-	-
DPBT [years]	64	-	-	-	-	-
SPBT [years]	42	-	-	-	-	-
Injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	401	401	422	412	411	449
NPV* [CHF/m2]	-80	-83	-67	18	16	40
IRR* [%]	1.1	1.1	1.4	2.8	2.7	3.0
DPBT [years]	37	37	35	29	30	28
SPBT [years]	26	27	26	22	22	22
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	432	418	427	452	426	459
NPV* [CHF/m2]	-36	-74	-46	51	14	39
IRR* [%]	1.9	1.3	1.8	3.2	2.7	3.0
DPBT [years]	33	36	33	27	30	28
SPBT [years]	24	26	24	21	22	22
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	439	424	445	580	565	595
NPV* [CHF/m2]	23	-15	-1	-64	-118	-89
IRR* [%]	2.8	2.3	2.5	1.7	1.0	1.5
DPBT [years]	28	31	31	34	36	34
SPBT [years]	21	23	23	24	26	25
No injection						
S1 – BIPV Conservation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	401	401	422	412	411	449
NPV* [CHF/m2]	-129	-127	-104	-28	-24	12
IRR* [%]	0.3	0.3	0.8	2.1	2.1	2.7
DPBT [years]	40	40	37	32	32	30
SPBT [years]	30	30	27	24	24	23
S2 – BIPV Renovation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	432	418	427	452	426	459
NPV* [CHF/m2]	-136	-121	-86	-44	-30	7
IRR* [%]	0.3	0.5	1.2	1.9	2.1	2.6
DPBT [years]	40	39	36	33	32	30
SPBT [years]	30	28	26	24	24	23
S3 – BIPV Transformation	**A**	**B**	**C**	**A**	**B**	**C**
Investment [CHF/m^2]	439	424	445	580	565	595
NPV* [CHF/m2]	-77	-62	-42	-159	-163	-123
IRR* [%]	1.3	1.6	1.9	0.6	0.5	1.1
DPBT [years]	35	34	33	38	39	36
SPBT [years]	26	25	24	27	28	26

Table 7-32. LCC indicator values obtained for the different scenarios and variants for Archetype 5, with and without injection possibility. * Horizon of 30 years for NPV and IRR calculations.

Indoor comfort

Results shown in Figure 7-67 indicate that the overheating limit of 100 hours/year is respected, and the sDA remains above 70% for all scenarios, with a reduction of 6% observed in scenarios S2 and S3 due to the external insulation.

Daylight Autonomy (DA_{100lux}) Map

E0 – Current Status

Overheating
OH: 50 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 79% of floor area
DF: 2.5%

S0 – Baseline

Overheating
OH: 61 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 79% of floor area
DF: 2.5%

S1 – BIPV Conservation

Overheating
OH: 78 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 79% of floor area
DF: 2.5%

S2 – BIPV Renovation

Overheating
OH: 57 hours/year*

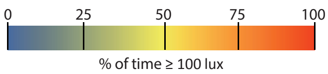
Daylighting
$sDA_{100lux, 50\%}$: 73% of floor area
DF: 1.9%

S3 – BIPV Transformation

Overheating
OH: 75 hours/year*

Daylighting
$sDA_{100lux, 50\%}$: 73% of floor area
DF: 1.9%

***OH**: Overheating hours at Ti>26.5°C*
***sDA**: Spatial Daylight Autonomy*
***DF**: Mean Daylight Factor*



** Requirements SIA 180 standard: limit to 100h/year at T>26.5°C*

Figure 7-67. Results of the overheating and daylighting study for Archetype 5.

7.4. Discussion

7.4.1. Results overview

The qualitative assessment of the different proposals indicates that the integration of BIPV elements does not in itself represent a barrier to the acceptance of projects. The fact that the acceptance level by practitioners for each scenario is non-homogeneous across the building typologies – e.g. the most desirable scenario differs according to the archetype – gives strength to the approach put forth in this thesis regading the development of a diversity of design scenarios. These results show that it is possible to design quality architecture that can be generally accepted by employing existing BIPV elements as a new construction material that *"actively"* participates in both defining the visual aspect / character of the building and improving its energy performance.

In addition to the visual representations of the different proposals, the quantitative results further support the idea that the integration of BIPV in renovation should not be perceived as a barrier, but as an opportunity to create a new architectural language. An architectural language defined by a global design strategy, from the will to maintain the original aspect or to reinterpret the existing architecture through the latest products and customisation techniques already available in the market.

A transversal analysis across the quantitative results allows to highlight the key aspects found for each group of indicators, common to all archetypes.

In terms of photovoltaic performance, we observe that although the orientation of the modules is not always optimal due to the pre-existence of the building, the carbon content of the electricity produced on-site is, in almost all cases, sufficiently low to allow recovering the impact of manufacturing the BIPV elements within their lifespan. For this to be the case, the selection of active surfaces to adapt the installation to the needs of the building plays a key role. Indeed, when all surfaces are taken into account (A-100%), both the levels of carbon content per kWh and the GHG emissions payback time are too high compared to the grid.

In this sense, the level of self-consumption is always lowest for energy-use scenario A-100%, reaching at its lowest a value of 9% (Archetype 1, S3, A-100%). The highest value obtained within scenarios of a same archetype range from 45% (Archetype 5, S1, C-Batteries) to 100% (Archetype 3, S1, C-Batteries).

To improve the SC and SS level, one of the ways we have explored is to replace the existing HVAC system with a heat-pump based system compatible with the photovoltaic installation. This type of high-efficiency equipment can be expensive depending on the required power. Our approach proposes first of all to prioritise the reduction of energy demand by improving the thermal efficiency of the building envelope. This measure has a non-negligible impact on the necessary power of the equipment to be installed. In this sense, the significant reductions observed in the power required for the HVAC system between the current status (E0) and the renovation scenarios – between 34% and 78% over all archetypes – highlight the important benefits of passive strategies as a first set of interventions.

The importance of an adequate location of the active surfaces considering both self-consumption and self-sufficiency, especially on buildings with a large façade area with respect to the available roof surface, is demonstrated particularly in a transformation approach (S3) where large installations are proposed from the design phase. The main benefits of applying this BIPV sizing methodology are:

- The robustness and simplicity of its application within the design process;
- Promoting a self-consumption approach, favourable in case of decreasing prices of injected electricity;
- Consistent with an economic and environmental impact analysis;
- Conducive to real carbon neutrality, rationalising the sizing in function of the building's needs to minimise the grid-injected energy;
- From a practical point of view, in terms of a BIPV installation implementation, the obtained solution is always an assembly of surfaces.

Through our BIPV sizing method, the identified SC-SS trade-off point in terms of irradiation threshold varies from 300 to 1'100 kWh/m²·year across all archetypes depending on the scenario. This range indicates to designers that is important to consider the façade surfaces.

These results challenge using a *"universal"* irradiation threshold range of 800-1'000 kWh/m²·year **[Compagnon 2004]**, a common BAPV sizing / positioning rule-of-thumb in order to maximise the energy production, assuming that the orientation/inclination of PV panels are optimal (e.g. south-oriented with an inclination using the latitude angle) and thus prioritising roof installations.

In terms of energy balance, the interventions of S0 are not sufficient for this scenario to reach both operational CEDnr and GWP targets. Only BIPV scenarios are able to do so, and more easily or by a larger margin when injection into the grid is possible. By applying the lower-impacting (over the architectural expression) BIPV scenario corresponding to S1-Conservation, the saving potential in terms of non-renewable primary energy (CEDnr) during the operational phase is of 94% (Archetype 1), 84% (Archetype 2), 68% (Archetype 3), 67% (Archetype 4) and 110% (for Archetype 5). GHG emissions savings achieve 97% (Archetype 1), 94% (Archetype 2), 87% (Archetype 3), 88% (Archetype 4) and 110% (for Archetype 5). The combination of strategies allowing to achieve these values vary depending on the archetype, from S1|B-Selection|HP for Archetypes 1, 2, 4 and 5, and S1|A-100%|HP for Archetype 3.

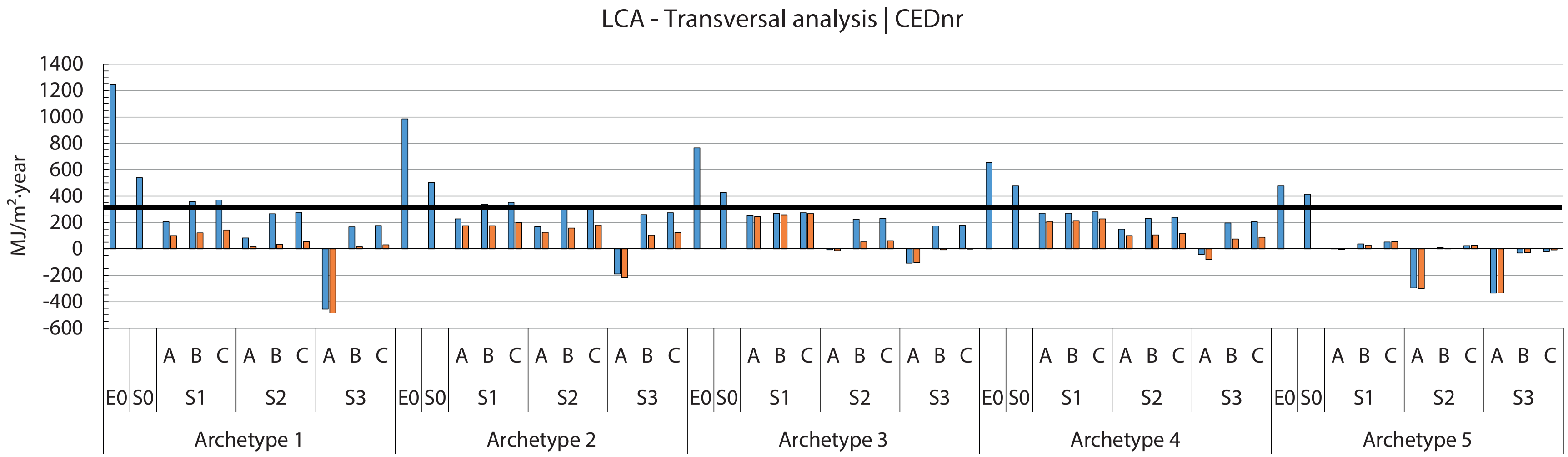
Figure 7-68. LCA results for all archetypes (injecting the electricity overproduced into the grid) in terms of non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP), considering construction phase (materials) and operational phase (consumption), taking into account the different energy-use scenarios (A- C), with or without replacing the exiting HVAC.

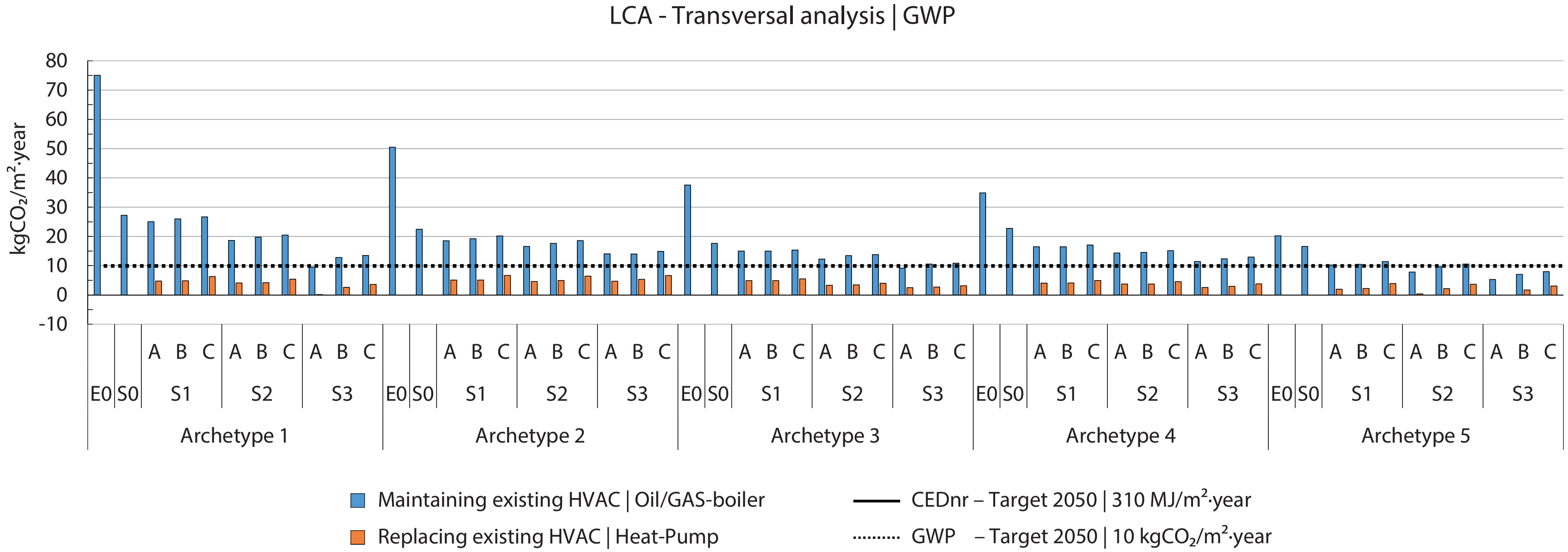
In terms of life-cycle assessment including operation and construction, results in terms of energy and carbon emissions payback times are respectively below 14 and 21 years, as shown in Table 7-33. EPBT is always shorter than GPBT, influenced by the energy and carbon content factors of the Swiss grid and the respective savings in energy and carbon emissions.

Archetype	EPBT range [years]	GPBT range [years]
1	1.4 – 4.4	2.0 – 5.9
2	2.5 – 8.3	3.7 – 12.5
3	2.9 – 5.8	2.1 – 9.2
4	3.1 – 7.2	3.7 – 9.9
5	3.2 – 13.5	6.8 – 20.8

Table 7-33. Ranges in energy (EPBT) and carbon emissions (GPBT) payback times across all scenarios for each archetype.

Although the 2'000-Watt Society targets were set as an objective only for scenario S3, replacing the fossil-fuel based HVAC system by an electric system (more compatible with the PV installation) brings all BIPV-scenarios below the targets (Figure 7-68).


LCA - Transversal analysis | CEDnr
MJ/m²·year
1400
1200
1000
800
600
400
200
0
-200
-400
-600
A B C A B C A B C
E0 S0 S1 S2 S3
Archetype 1
Archetype 2
Archetype 3
Archetype 4
Archetype 5


LCA - Transversal analysis | GWP
kgCO₂/m²·year
80
70
60
50
40
30
20
10
0
-10
A B C A B C A B C
E0 S0 S1 S2 S3
Archetype 1
Archetype 2
Archetype 3
Archetype 4
Archetype 5
Maintaining existing HVAC | Oil/GAS-boiler
Replacing existing HVAC | Heat-Pump
CEDnr – Target 2050 | 310 MJ/m²·year
GWP – Target 2050 | 10 kgCO₂/m²·year

As one of the major barriers to BIPV installations in buildings is related to financial aspects, below are the points that we believe are most important to highlight. In terms of cost, the discounted payback time is consistently shorter for BIPV scenarios than for current practice renovation without BIPV (S0 scenario). Results across the different case studies highlight that the best cost-effectiveness is achieved with BIPV scenarios. Taking into account the global investment cost after discounting the subsidies currently available (for improvement of the building envelope and for the photovoltaic installation), as well as the tax reduction, results in Table 7-8 show that staying with the S0 scenario versus implementing a BIPV scenario like S1-Conservation does not make sense, especially knowing that the additional cost allowing to achieve the 2'000-Watt Society varies only by 0.5% (for Archetypes 3, 4), 9% (for Archetype 1), 10% (for Archetype 2) and 19% (for Archetype 5).

Archetype	Floor area (m^2)	Investment cost (CHF/m^2)			
		S0	S1	S2	S3
1	788	715	789	826	1'135
2	847	830	923	941	1'333
3	4'415	448	451	481	645
4	5'263	360	362	370	536
5	4'417	322	399	476	627

Table 7-34. Globalised investment cost of the S0 scenario compared to BIPV scenarios with all possible active surfaces considered (A-100%). Prices normalised per floor area.

As exposed in Chapter 3, there are some preconceived ideas related to the integration of BIPV elements on the building envelope. Observing the results obtained for the internal rate of return (Table 7-35) using conservative assumptions (e.g. especially in terms of BIPV prices that are expected to go down even more), for practically all BIPV scenarios implementing a well-sized installation (B-Selection or C-Batteries), the IRR goes from 3.2% to 7.5% for a 30-year horizon, depending on the archetype.

Archetype	Max. IRR [%]	Combination scenario
1	6.2	S1 | B-Selection | HP
2	4.0	S1 | C-Batteries | HP or S2 | A-1000% | HP
3	7.5	S2 | C-Batteries | HP
4	6.6	S2 | C-Batteries | HP
5	3.2	S2 | A-1000% | HP

Table 7-35. Maximum internal rate of return (IRR) obtained and the variants combination making it possible.

The maximum IRR is achieved for scenarios S1 and S2 depending on the Archetype. However, it is interesting to verify what are the values when an S3 approach is applied (Table 7-36). Although the IRR can be an important parameter to convince an owner to carry out one renovation strategy or another, this purely economic parameter should not be considered separately from the rest of the parameters (e.g. energy saving, energy bill, environmental impact ...).

Archetype	IRR [%]	Combination scenario
1	4.7	S3 | C-Batteries | HP
2	2.4	S3 | C-Batteries | HP
3	5.7	S3 | C-Batteries | HP
4	4.6	S3 | C-Batteries | HP
5	1.7	S3 | A-1000% | HP

Table 7-36. Maximum internal rate of return (IRR) obtained for scenarios S3.

With the final group of indicators, indoor comfort criteria were verified. Since renovation strategies involve greater insulation and airtightness of the building envelope, care must be taken to mitigate the risk of overheating, by ensuring an adequate aeration strategy and solar protections. The simulations carried out indicate that the limit in terms of overheating hours is respected by all the proposals. In terms of daylighting potential, the external insulation systems cause a decrease in daylight autonomy between 1 and 7%. In most cases, the acceptable reference values (sDA of 55% **[IES 2013]** and DF of 2% **[Carrier et al. 2000]**) are respected before and after the interventions.

From all results, we highlight that:

- Energy renovation projects without PV integration are no longer an option if we want to achieve long-term carbon and energy targets;
- A selection of active surfaces adapting the installation size to the building needs prioritising self-consumption could help to reach carbon neutrality avoiding at the same time the intrinsic problem linked to decreasing prices of injected electricity and incompatibilities with the existing grid;
- The integration of batteries could have a key role in achieving the Swiss targets if the injection into the grid is not possible.

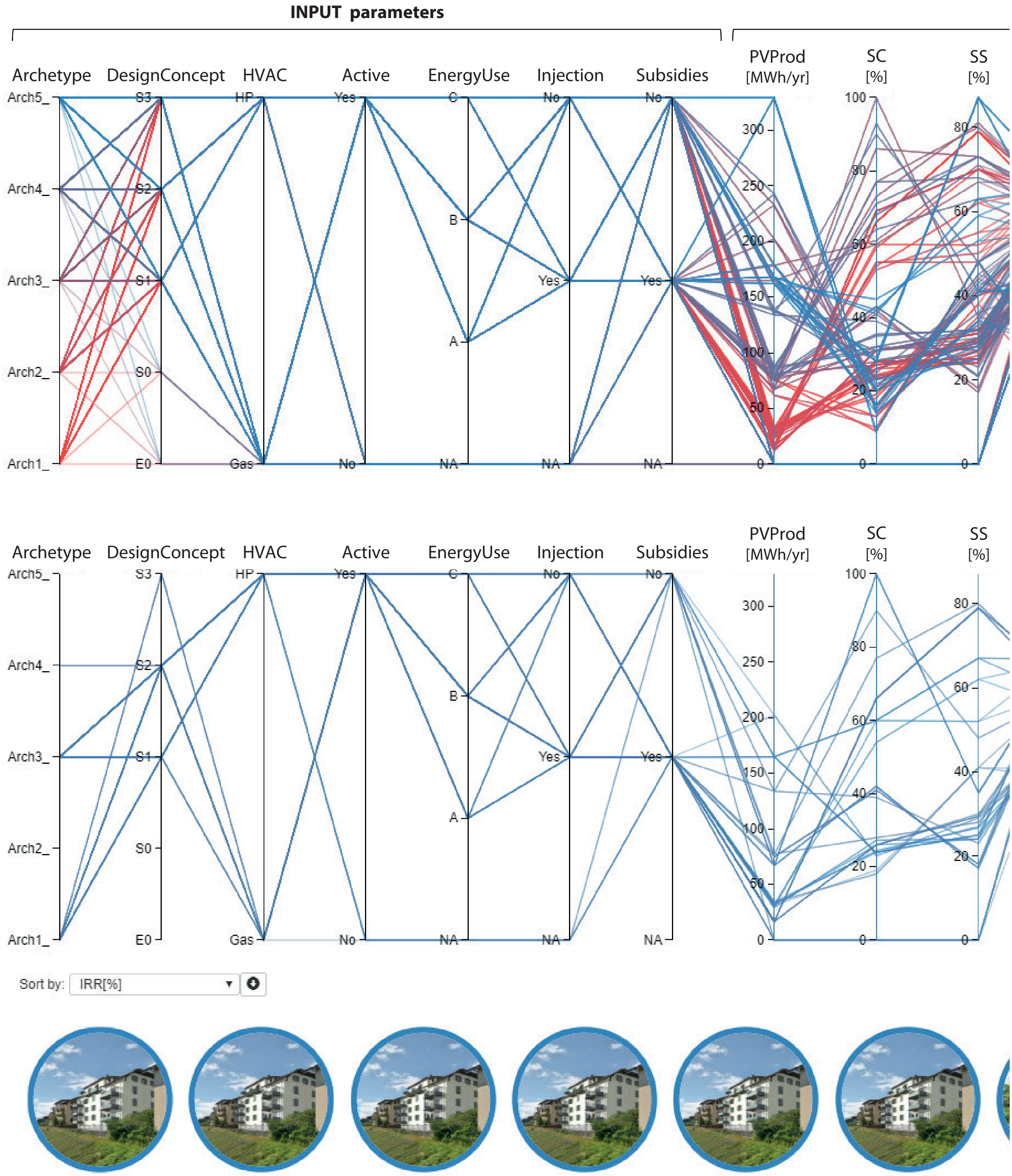
7.4.2. Exploration of design variants

To further investigate the influence of the different parameters that define each scenario, as well as the relationship between those parameters and the performance indicators, parallel coordinates plots (PCP) can be used, offering a synthetic view of all results. Using the interactive Design Explorer online tool **[Thornton Tomasetti 2018]**, a PCP holding results for all archetypes and scenarios was produced, as shown in the top image of Figure 7-69.

The PCP displays each evaluated scenario as a line connecting different vertical axes that each correspond to an input parameter defining the scenario (e.g. energy-use scenario A-B-C) or output parameter, i.e. assessed indicator including GWP, CEDnr, IRR, etc. The online tool allows interacting with the chart by selecting intervals of values for one or multiple axes, as illustrated in the bottom image of Figure 7-69 for the IRR indicator. Scenarios that fall within the highlighted range are shown and the others filtered out of the graph. For an IRR of at least 5% or higher, we observe that only BIPV scenarios (S1-S3; see DesignConcept axis) are visible, meaning that only those options fulfil this condition. When filtering based on the GWP indicator to view scenarios that respect the 10 $kgCO_2/m^2 \cdot year$ target (2'000-Watt Society) in Figure 7-70, we see once again that only BIPV scenarios are preserved. The full description of two example scenarios with GWP close to zero are shown at the bottom of Figure 7-70. The different PCP (individual per archetype and for all archetypes) are accessible at the folowing URLs:

DesignExplorer URL with a selection of parameters for all Archetypes.

Archetype 1	https://goo.gl/2E1GWu
Archetype 2	https://goo.gl/brqxXj
Archetype 3	https://goo.gl/PBMszH
Archetype 4	https://goo.gl/k5p4Yo
Archetype 5	https://goo.gl/WKKgWx
All Archetypes	https://goo.gl/nUgjjX


INPUT parameters
Archetype
DesignConcept
HVAC
Active
EnergyUse
Injection
Subsidies
PVProd [MWh/yr]
SC [%]
SS [%]
Arch5_
Arch4_
Arch3_
Arch2_
Arch1_
S3
S2
S1
S0
E0
HP
Gas
Yes
No
C
B
A
NA
No
Yes
NA
No
Yes
NA
300
250
200
150
100
50
0
100
80
60
40
20
0
80
60
40
20
0
Archetype
DesignConcept
HVAC
Active
EnergyUse
Injection
Subsidies
PVProd [MWh/yr]
SC [%]
SS [%]
Sort by: IRR[%]

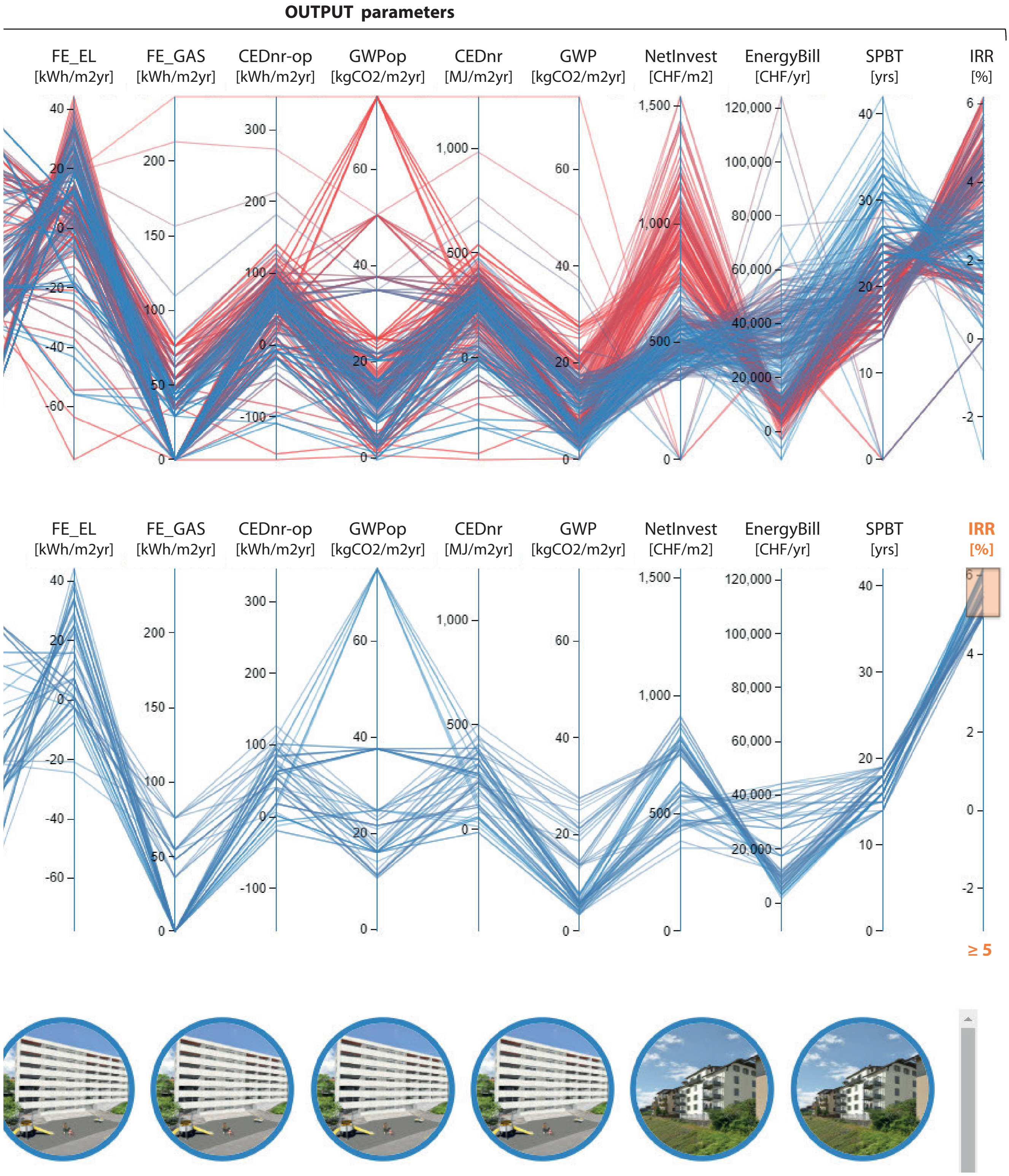


Figure 7-69. Parallel coordinates plots showing results (for a selection of indicators) for all archetypes and variants (top) and for scenarios with an IRR larger than or equal to 5% (bottom).

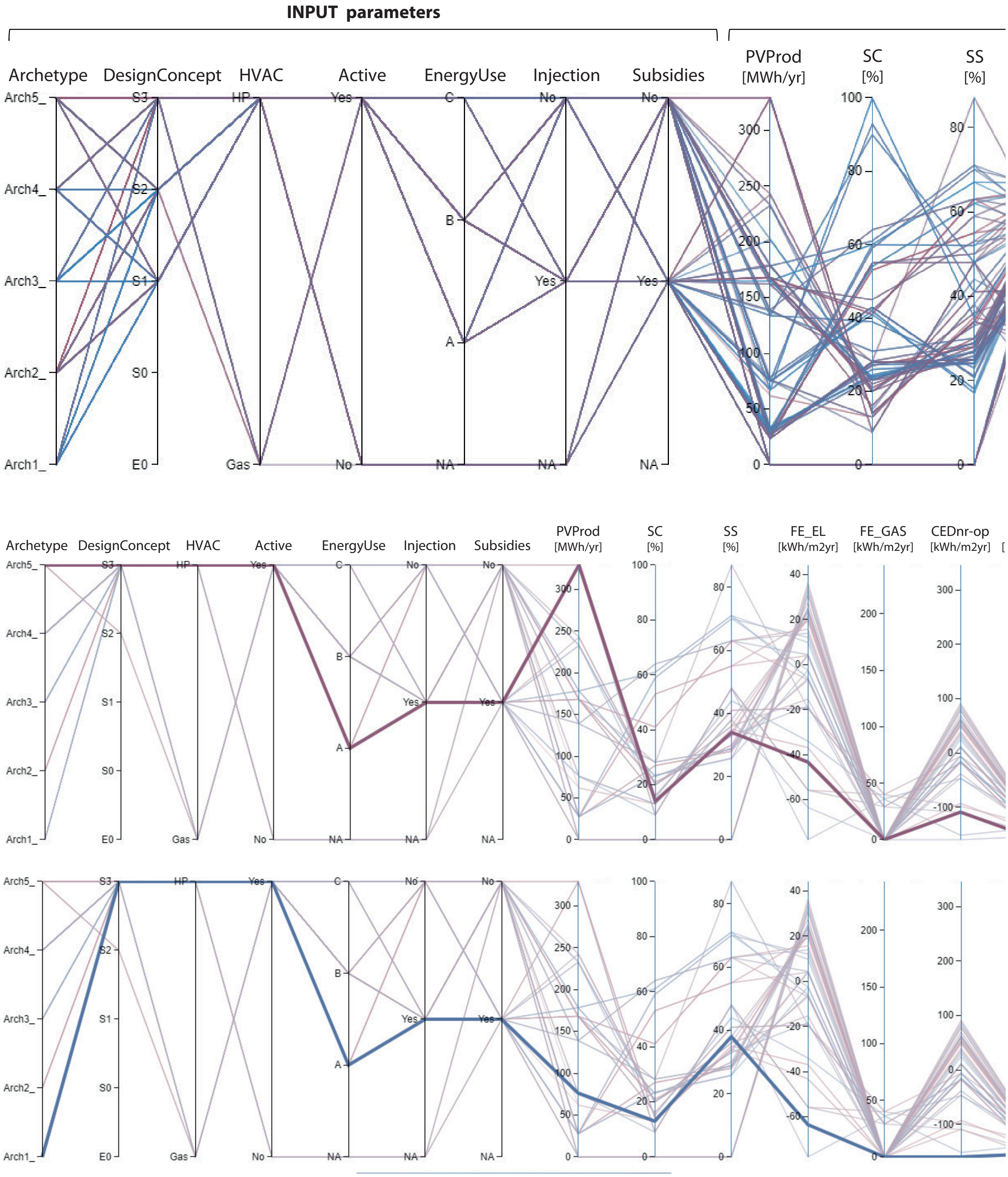

INPUT parameters
Archetype
DesignConcept
HVAC
Active
EnergyUse
Injection
Subsidies
PVProd [MWh/yr]
SC [%]
SS [%]
FE_EL [kWh/m2yr]
FE_GAS [kWh/m2yr]
CEDnr-op [kWh/m2yr]

Figure 7-70. Parallel coordinates plots showing results (for a selection of indicators) for scenarios with a GWP below or equal to 10 $kgCO_2/m^2\cdot year$ (top) and for two example scenarios (Archetypes 5 and 1) reaching carbon neutrality (bottom).

8. Conclusion

This conclusion is structured in four main parts. First, the main achievements and contributions of this thesis are summarised, followed by a return on the research question introduced in Chapter 2. Recommendations are then formulated, prior to concluding with perspectives in terms of the next steps envisioned (in relation to limitations of the work), as well as a broader outlook.

8.1. Achievements and contributions

The decarbonisation of the built environment is crucial to mitigate the consequences on the climate. In order to do this, policies and associated regulations put existing buildings in the spotlight. These are inherited from times when the requirements in terms of energy efficiency, energy consumption, and CO_2 emissions were still inexistent or in a rudimentary phase. Today, this is no longer the case, and the climate emergency is leading to a change of paradigm that affects all areas of our society. The decarbonisation of the built environment happens for a significative part through the renovation of buildings, following a mid- to long-term life-cycle approach.

In order to address this, the present thesis has begun by investigating the literature outlining the research framework, which brings together building renewal processes and photovoltaics in architecture. It appears a real lack of holistic approaches for addressing renovation projects of residential buildings integrating BIPV, not only from a construction / functional point of view, but also in terms of coherence of the the design approach with the building architecture, its context, and its energy needs, as well as in terms of environmental and economic implications.

A four-phase methodology was defined, starting in Phase 1 with a top-down urban-scale analysis carried out on a representative city of the Swiss plateau. Through this investigation, it was possible to gather an understanding of the composition of the existing residential building stock, and propose a classification framework based on the combination of key building features (construction period, adjacencies, roof type, height, etc.). This classification enabled defining five archetypal situations to serve as guides for selecting relevant and representative case studies (i.e. existing buildings).

Phases 2 to 4 of the methodology were then illustrated through their application on these five case studies. In Phase 2, a detailed analysis of the selected buildings including their constructive details served to determine the envelope features and fully characterise the current status of each building (E0-Current status). The diversity in terms of architecture as well as in the observed envelope performance, e.g. high thermal transmittance, simultaneously reinforced the necessity of renovating these buildings and the pertinence of their selection.

Through Phase 3, we carried out the development of a series of renovation scenarios on each case study: S0-Baseline, corresponding to the current practice according to the minimum legal energy performance requirements, and the three renovation scenarios with BIPV integration from a global design perspective, with incremental levels of intervention (S1-Conservation, S2-Renovation, and S3-Transformation). Developed down to the constructive level of detail, computer-generated images were produced, showing the appearance obtained after the implementation of each renovation scenario, as well as the distinct translation of a same set of strategies over the different case studies. This architectural design-driven phase brought out the flexibility offered by existing BIPV products and customisation techniques in relation to meeting a varying level of integration.

In Phase 4, a multi-criteria assessment including both a qualitative and quantitative facet was conducted. The qualitative assessment allowed evaluating all proposals subjectively by a committee of experts. The collected feedback supported the endorsement of the scenarios by the stakeholders as credible solutions, and indicated where further refinements would be desirable.

The complimentary quantitative assessment has offered a view of the performance of the different scenarios through indicators related to resource and energy use, environmental impact, economic aspects, and occupant thermal and visual comfort. Finally, a comprehensive BIPV renovation assessment tool was developed, incorporating various configurable parameters and enabling the comparison of results for the different combinations of variants for each archetype and scenario.

The application of all these phases on the distinct case studies provide architects, PV installers and public authorities with a palette of solutions, based on a design concept underlined by an understanding of the specific features and needs of each building, and that prioritises architectural quality. In that way, the proposed solutions balance common and case-specific characteristics that could be adapted and transposed in other contexts.

By providing this range of assessed design propositions, this thesis aims to support practitioners during the design-decision process and enhance their capability to respond to the energy requirements, by bringing to light key aspects related to the use of BIPV elements in renovation projects. These elements will encourage the adoption, by practitioners, of BIPV as a new expressive and construction material to be more easily used and consequently integrated in their own designs. In the following paragraphs, an emphasis is placed on linking the final results with the achievements / contributions enunciated at the end of Chapter 3.

From the urban-scale analysis, we saw that a majority of the residential buildings was built before 1985. Results for the E0-Current status scenarios show that the selected buildings have final energy consumptions (for heating, DHW, lighting and appliances) between 99 and 262 kWh/m^2·year. Comparing these values with the results obtained for the S0-Baseline scenarios, the saving potential achieves between 19% and 64% depending on the archetype. From these results, we can contemplate the considerable saving potential contained within the whole residential building stock of Neuchâtel.

Although the objective of this study is not the extrapolation of results to the entire park of buildings, as this would require studying more typologies, it is still interesting to do the exercise on the buildings that fit well with the archetypes definitions, to have broad estimates of the potential energy and emissions savings.

After excluding the highly protected heritage buildings, we arrive at 2’300 residential buildings that have been constructed in Neuchâtel up to 2005. Within these 2’300 buildings, there are 1’067 buildings that exactly match the combination of criteria that have led to the classification by archetypes.

Scaling-up the LCA results obtained for the different archetypes to that set of buildings, the savings in terms of primary energy (CEDnr) and GHG emissions that can be achieved varies depending on the renovation strategy. By applying a S0 renovation without integration of BIPV, the savings would be of 42% and 50% respectively. On the other hand, if BIPV renewal strategies are applied, savings can range between 71%-122% (in CEDnr) and 85%-95% (in GHG emissions).

Coming back to our building-level study, despite the significant potential demonstrated by the S0 scenario, results show that current practice does not allow to reach the 2'000-Watt Society objectives for 2050, especially in terms of CO_2 emissions. More specifically, we highlight that renovated buildings that comply with the current standards (e.g. SIA 380/1:2016) emit during the operating phase between 2 to 5 times more CO_2 and consume between 1.5 and 2 times more non-renewable primary energy than the requirements of the 2'000-Watt Society. The mandatory regulation (SIA 380/1:2016) focuses on the reduction of energy demand, which is absolutely necessary as a first step towards a decarbonisation of the built environment, but it is essential to go further. The exercise carried out in this thesis demonstrates that, in addition to reducing energy losses through the thermal envelope of the building, on-site electricity generation with a much lower environmental impact than the grid can offer a feasible path.

Starting from the assumption that renovation will be triggered more and more to maintain building value, and will be driven by new regulations for climate protection, it is important to analyze energy renovations with the integration of photovoltaic energy, and not settle for complying with current standards and practices. Conducting this exercise in anticipation to the evolution of the norms, that shall integrate decarbonisation strategies in the years to come, allows to have an idea of what these new regulations should focus on, e.g. promoting high levels of self-consumption rather than fixing minimum installed power per m^2 of floor area. In addition, the alliance between the renovation process and the integration of photovoltaic energy from an early design phase offers a broad spectrum of benefits that is not limited solely to energy savings.

Existing BIPV products and innovative customisation techniques offer the possibility to develop a new architectural language, allowing a respectful dialogue with the urban context of the building. By setting, from the beginning, a global design strategy in relation to this context, architects have all the tools they need to achieve a better acceptance of renovation projects with active façades and roofs.

The design proposals, presented at the workshop, employ BIPV elements as a new expressive and construction material based on different levels of interventions, generating a new architectural language where visible products are made part of the envelope. For older buildings, such as Archetypes 1 and 2, which display a characteristic language and materiality (e.g. decorative elements, large inclined roofs, typical proportion of windows), conservation (S1) or mimicry (S2) strategies are best accepted. However, more recent architecture with an imposing materiality (e.g. concrete or apparent brick) such as Archetypes 3, 4 and 5, easily admit all design approaches with a tendency to solutions of conservation (S1) or transformation (S3). Therefore, the acceptance of this type of proposal does not seem to be a major problem.

Yet, the acceptance is high above all when a conservation approach (S1) – respecting the original aspect of the building – is proposed. However, when the design follows a mimetic approach (S2), trying to imitate the existing appearance, but with a high energy performance objective, other aspects come into play, such as the complexity of the constructive solutions or the small size of the active elements that make the installation more complicated and consequently more expensive.

Overall, findings from the qualitative assessment indicate that BIPV does not in itself represent a barrier to the acceptance of projects. Through this new expressive and construction material, designers have the possibility to create quality architecture with a high level of acceptance. This opportunity of developing a new architectural language, while improving the building's energy and financial performance, is theirs to seize.

Yet, there is a consensus about a general lack of knowledge on what BIPV can offer, from both architects and contracting authorities (e.g. owners, institutions). This may be one of the reasons why the workshop participants consider that public support for the dissemination of BIPV is not sufficient. However, the quantitative analysis shows that the existing subsidies are sufficiently effective to mitigate the effect of the high prices of these new products, until demand increases progressively.

Regarding the investment cost required for a BIPV installation, results bring out that by adding all the available subsidies (cantonal, communal and tax reduction), the investment can be reduced by 27% to 67% depending on the type of installation and its size. Likewise, by reporting the effect of subsidies on the entire project (renovation with an integrated active envelope), current subsidies allow a cost reduction of 10% to 28%.

Coming back to the workshop, despite the endorsement shown for prefabricated solutions and the evolution of the BIPV domain in general, the answer to the question about the possible influence of the research in the professional practice of participants does not quite reflect the same enthusiasm. However, it is important to note that 77% of respondents are receptive to changes toward integrating active solutions into their own projects. This reinforces the idea that this type of research can play an important role in the dissemination of BIPV knowledge so that at least one detailed study is carried out before the easiest decision is made, which is to repeat the usual.

This thesis provides useful information for designers and the different actors involved in the renovation process to assess the relevance of the different proposals at the constructive, aesthetic, energetic, environmental and economic levels. This information is intended to assist in reaching compliance with the Energy Strategy 2050, by providing a guide with concrete strategies and reference values for a better integration of BIPV, by applying the proposed methodology on other projects.

A major contribution of this work is to have shown and addressed the complete thought process that should be carried out in the context of a renovation involving BIPV, linking the urban to the constructive detail scales. Indeed, the robust analysis methodology, core contribution to the research field, allows the in-depth study of renovation scenarios with BIPV at the architectural / construction detail level while generating a database for subsequent extrapolation at the urban scale. The thesis also contributes to open up new perspectives in the field of *"research by design"* in architectural research, in particularly in the explorations of the interactions between architectural design and sustainability issues. The main limitations and shortcomings of the thesis are addressed in the future work section below.

8.2. Return to the research question

Photovoltaic elements have been used on buildings for some time. The initial approach has been to treat PV elements as an electrical system to be added on the most exposed surfaces of the building, used as physical support, and with the goal of maximising production and inject the PV electricity into the grid. In this BAPV approach, the PV elements are foreign to the building and do not contribute to its architectural coherence and constructive language.

Reinterpreting these elements from a constructive aspect has led to the BIPV concept, where PV products fulfil the function of an external envelope layer and therefore become constructively integrated. This concept is well known, accepted and already applied for new buildings where, by the simple fact that the building itself is conceived from scratch, the integration of this type of elements can be done in a relatively natural way.

When PV elements begin to form the building's external layer, they do not only contribute to the constructive aspect, but also to the architectural features by participating to define the building expression. Architects are then naturally concerned and represent the first actors concerned by the BIPV concept and consider such products no longer as systems, but as an architectural material that is able to contributes to the task of designing.

For new buildings, this architectural integration is typically supported by adopting a prefabrication approach, so that the design of the building (and its façades) already integrates the requirements imposed by photovoltaic elements as if they were any other façade element.

However, in urban renovation projects, this BIPV concept cannot be applied in the same way and, therefore, is not yet well or fully defined. In this thesis, we have attempted to cast light onto this subject by doing the exercise of confronting BIPV with real buildings, showcasing the architectural results and comprehensively assessing the proposed interventions.

Through a transversal analysis of the results of this research, we specifically observe that:

- the global approach is compatible with a variety of design objectives allowing to adapt the BIPV renovation strategies to features proper to each building and its context;
- the environmental impact of BIPV elements is recovered within the manufacturer warranty period (25-30 years);
- an adequately-sized BIPV installation leads to high levels of energy independence and self-consumption, reducing stress on the grid;
- at the economic level, BIPV strategies help to self-finance the whole renovation project when considering the benefits produced by both the energy self-consumed on-site and the revenues perceived by injecting the overproduction into the grid

These outcomes lead us to provide an answer to the research question: ***"What role can BIPV have in the architectural design processes of residential building renovation?"***

In the context of the energy transition, BIPV can become in certain cases a trigger for renovation processes of residential buildings in urban areas, as the holistic integration of BIPV elements can bring a project over a tipping decision point, often related to the cost-effectiveness of the intervention.

Answering the research question simultaneously reinforces the underpinned hypothesis that **"BIPV can be simultanesously considered as one of the significant contributions towards low-carbon buildings and as integral part of the architectural design strategies in urban renewal processes"**.

Indeed, in the context of the energy transition, without pretending to be the only way to do so, the approach put forth in this thesis can help not only to achieve the 2'000-Watt Society targets, but also to launch renovation projects which would otherwise have been carried out at a partial degree (missing out on the full potential) or not have been conducted at all.

As demonstrated by the quantitative results, the cost-efficiency – taking into account the life cycle of the renovation project – reaches values likely to be acceptable to any owner or investor. The BIPV installation is not only an efficient contributor toward achieving the environmental objectives, but also has a **subsidising effect** on the whole renovation project.

Moreover, from an architectural design perspective, the developed scenarios support the idea that it possible to integrate BIPV elements at different degrees, according to the design intent, considering standard and customised sizes and appearances. In that sense, as other sustainability issues, BIPV can become a real *"raw material"*, in a conceptual and expressive way, with which architects can play in their design process.

8.3. Recommendations

Results from our case studies indicate that renovation projects in which the building envelope is improved up to a high level of energy efficiency are necessary, but not sufficient to achieve the objectives of the Energy Strategy 2050. Integrating renewable energy through the BIPV concept appears as a promising option towards achieving these objectives.

Current energy efficiency standards are far from the 2050 targets. Existing regulations should consequently be reviewed so that legal requirements are brought up to the level of the environmental objectives, among others, by taking into account the multiple benefits of BIPV renewal scenarios.

From the outcomes of this work, it appears that the most appropriate way to integrate photovoltaic elements into the building envelope in renovation projects consists in ensuring that the integration is envisioned from the initial design phases, and through a holistic vision of the renovation project that takes into account both the energetic and constructive requirements as well as the design objectives. The opportunity of complete interventions must be explored, analyzed and proposed, combining compatible passive and active (on HVAC systems) strategies, along with the integration of PV elements following a global concept where active surfaces are selected in order to harmonise the electricity production with the real needs of the building. The integration is as such understood as a symbiosis relationship, where the building offers exposed surfaces and the active elements offer protection, as well as electricity at low environmental impact and affordable price, to be used directly by the building.

Results from the comparative energy-use scenarios lead us to the conclusion that combining passive and active strategies with BIPV elements located according to a selection of active surfaces, based on a trade-off between self-consumption and self-sufficient ratios (B-Selection), is likely to ensure an attractive compromise between energy performance, environmental impact and cost-effectiveness.

As design decisions can have a major influence on the final holistic performance of the building, limiting or helping to achieve the objectives for 2050, we recommend to conduct a study from the early design phase, to explore the benefits of an *"active"* renovation integrating BIPV elements in adequation with the main design concept of the whole project. To help understand this concept, it is best to picture a concrete example.

We imagine that an architect is confronted with the renovation of a building from the 1920s, similar to the Archetype 1, with the mission of proposing a project to achieve the objectives of the 2'000-Watt Society. If the project does not involve a change of energy source (e.g. substituting the oil-boiler by a heat-pump), the designer only has the option of applying a transformation approach integrating active elements extensively to comply with the limit in terms of GHG emissions. However, if the architect includes in his/her concept the overall systems, and proposes a new system that takes better advantage of the BIPV elements, this will allow more design flexibility.

Using the results offered by this thesis, the designer knows beforehand that if a well-adjusted installation (B-Selection) is proposed using the best exposed surfaces of the roof, the project is more likely to achieve the objectives. In addition, if he/she also decides to use the available surfaces on the balconies, integrating the BIPV elements as a railing element, this decision has the potential of leading to achieving practically carbon neutrality. Moreover, these interventions correspond to beneficial economic results, with around 6% of IRR at a 30-year horizon. Results from the LCC indicate to the designer that this kind of investment requires mid- to long-term horizons, between 20 to 25 years, depending on the scenario.

For rental buildings, the modalities for allocating the savings from self-consumped and/or exported PV electricity between owner (investor) and tenant (benefiting from lower charges) should be addressed to encourage investments in BIPV.

The thesis's findings also demonstrate the importance of subsidies that can help overcome certain economic barriers. Furthermore, the allocation mechanism should be based on expected performance and architectural quality, captured through indicators that are adjusted to the building's needs and considering its context, etc. (e.g. architectural integration, self-consumption rate, carbon content factor), instead of a fixed peak power independent of such considerations.

Although emphasis has been repeatedly placed on architects throughout this thesis, the outcome of this research can contribute to spread awareness of the BIPV potential around the addressed issues among other stakeholders, and in particular building owners, by demonstrating the interest there might be in a BIPV-integrating renovation of their building. Knowledge on (BI)PV could be difused into the education and training of the different concerned actors, and means to foster better collaborations between them.

8.4. Perspectives

To conclude this thesis, current limitations and associated further steps are discussed, followed by an outlook on the broader application potential of this work.

8.4.1. Future work

While this research has involved multiple topics through an interdisciplinary approach, a related shortcoming lies in the limited depth at which it was possible to explore all the themes relevant to the subject treated, within the scope of a thesis. Further investigation avenues and extensions of the research are as such introduced below.

Adding new case studies

Future research could involve adding case studies by identifying other archetypal buildings, complementing our five archetypes in terms of construction period, architectural features, etc.

Considering that the number of single-family houses in periurban areas is substantial, it could be interesting to apply the methodology in order to assess the impact of BIPV also on this type of buildings, notably in terms of decarbonisation potential.

Combined BIPV and enlargement strategies

Currently, many renovation strategies of multi-family buildings aim to maximise the economic profitability by adding new floors to increase the rented area. It would be interesting to see what can be achieved by both enlarging the building and implementing BIPV strategies. In that context, further strategies could be envisioned, for instance more changes to the original aspect and structure of the building, following the intention behind the S3-Transformation scenario.

BIM integration

The assessment methodology could be implemented into a building information modelling (BIM) environment as proposed in **[Mohd-Nor et al. 2014]**. New functionalities in the latest version of the DesignBuilder software that improve the interoperability with BIM tools, using gbXML exchange files, could be used to obtain results automatically from the digital model when changing strategies at the architectural level. In addition, a BIM implementation can support the facility management once the project is completed, by allowing long-term monitoring and comparison of simulation results with actual results.

Uncertainty in assumptions and sensitivity analysis

Assumptions and simplifications had to be made to accomplish the quantitative assessment. These concern, for instance, energy prices, efficiency and environmental impact of BIPV technology, feed-in-tariff, public incentives, environmental impact of the energy from the grid, etc. However, while results are dependent upon those underlying values, the set of tools, methods, and overall workflow remain valid. Moreover, the Excel-based BIPV renovation assessment tool allows changing each hypothesis to view its influence on the results.

Still, consideration of the uncertainty regarding these values could be futher incorporated into the workflow, by implementing the means to conduct an extensive sensitivity analysis study.

Hourly impact conversion factors

Typical calculations are based on static conversion factors between final and primary energy and between final energy and CO_2 emissions, such as those from KBOB [**KBOB 2016**] that are used in this thesis. However, some studies have started to compare these standard values (representing mean values) with hourly-step real data from the grid. **[Vuarnoz et al. 2018]** shows that in terms of CED, the KBOB value of 2.52 kWh_{NRPE}/kWh represents a good average over the year, but in terms of GWP, the KBOB 2016 value of 0.102 $kgCO_2$/kWh is too low compared with the mean of the GWP factors over the year (about 0.200 $kgCO_2$/kWh for 2016). In the same line of thought as the uncertainty considerations mentioned above, refinements could be brought to the workflow to provide the possibly of replacing static values by a timeseries version of the data when available.

Carbon-based energy management

In addition to selecting the right active surfaces to size the installation reasonably according to the demand of the building, it could be of interest to analyse the effect of demand-side energy management to control some appliances in order to increase SC and SS without considering batteries. Supplementary energy-use scenarios could be added to the study, such as the possibility of having a microgrid at the neighbourhood scale and to implement energy management systems that allow optimising the energy consumption to minimise the carbon impact, by selecting in real-time the *"cleanest"* energy source (grid, BIPV installation, energy stored in batteries or energy generated from a neighbour building that is better exposed).

Explore the implementation of reused PV elements and batteries from electric vehicles

As seen inTable 3 6, 80% of c-Si modules have a reuse potential of 80% **[Sykorova et al. 2018a]**. This information could be implemented into the analysis, which would mainly influence the life-cycle assessment. In addition, the battery recycling industry is beginning to adapt to a probable reality where mobility in general becomes electric, leading to a large consumption of batteries. Today, there are already some studies on the reuse of vehicle batteries for stationary use as required by buildings. According to **[Richa 2016; Tsiropoulos et al. 2018]**, the reuse of li-ion batteries can reduce by 15% the environmental impact (CED and GWP) compared to the use of new batteries. It would be interesting to enter these data to see how it affects the LCA results of our case studies.

Extended acceptability evaluation

Results from the qualitative assessment, due to the relatively small sample of stakeholders who took part in the workshop, cannot be generalised. Furthermore, no citizens were consulted, despite the fact that they represent concerned actors who have the potential of blocking the execution of a project through the public consultations, a key step in the process in Switzerland.

The qualitative assessment of the proposals could thus be further investigated by sollicitating the opinions of a larger pool of not only professionals, but also citizens. The protocol for gathering the participants' inputs could also be refined through collaboration with social scientists specialised in qualitative research methods.

8.4.2. Outlook

From a wider perspective, further application and development paths are envisoned.

Transposition into legal framework

This thesis could contribute to the elaboration of a new legal framework for performance-based solar urban planning in Switzerland, starting by proposing directives adapted to the specific case of the city of Neuchâtel, where the current master plan will soon be updated. This revision would indeed provide a great opportunity to apply the outcomes of this work, for the promotion of quality renovation strategies, integrating BIPV and respectful of the context.

Diffusion and implementation into design decision-support tool

The diffusion of the research findings towards architects' associations, large building portfolio owners – both institutional and private – and public authorities including urban commissions could accelerate the transfer to the practice.

Furthermore, the developed methodology could be implemented into a proper tool, such as an online platform, accessible by all parties and simultaneously becoming a collaboration and communication tool between architects, engineers, manufacturers, suppliers, owners, financing bodies, etc. *"Packaging"* all phases of the research into an applicable workflow would enhance the potential for its uptake in practice and the dissemination of the work. The illustration of the method on real case studies could become an integral part of the project evaluation protocol by the authorities.

Application in real renovation projects

Given the motivations behind this work and the underlying practice-oriented research approach, we aspire to apply the methodology in the context of a real renovation project – i.e. a pilot application – on an existing building located in the city of Neuchâtel or in other urban areas in the near future. Carrying out this application would provide valuable insights on knowledge transfer issues for research to innovative practices, contributing to further refining the method and enhance its applicability.

Towards a new paradigm for the design of active façades

In light of the growing societal awareness around energy issues, with solar energy increasingly perceived as a significative contribution to address air pollution and climate change, along with technological developments and evolution of cost and policies, it appears that new paradigms are emerging and open a wide range of opportunities for integrating active components into building renovation strategies. In the context of energy transition, a new field opens up for the architectural design in the building renovation sector. In that sense, the present doctoral research constitutes a solid base encouraging the pursuit and the deepening of design explorations – through research projects and innovative practices – toward a quantitative and qualitative development of that domain.

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10. Annexes

The following sections provide complementary information about:

- Building envelope characteristics (10.1)
- Thermal bridge analysis (10.1)
- Physical properties of materials used (10.1)
- Assumptions for the generation of the different energy models (10.2)
- An economic verification of the proposed BIPV sizing method (10.3)
- Data for the environmental impact calculation (10.4)
- Detailed information on the global cost estimation (10.5)
- Definitions and formulas used (10.6)
- Example of detailed LCA results for Archetype 1 (10.7)

10.1. Building envelope characteristics and thermal bridge analysis

The information presented in this section complements the data given in Chapters 5-7 regarding the composition and performance of the building envelope of each scenario.

First, the physical properties of the materials used to define the building envelope are listed. Second, the calculation method and tools used for the thermal bridge, and condensation and mould risk analysis are described. The detailed materials description (table format) and thermal bridge analysis results are then showed for each archetype. For the thermal bridges, the analysis is described in more detail in the section of Archetype 1, and more succinctly in the subsequent sections (Archetypes 2-5) to limit repetitions.

10.1.1. Physical properties of materials used

Table 10-1 lists the main physical characteristics of the materials used for the energy model and thermal bridges calculations.

	Density [kg/m³]	Specific heat [j/kg·K]	Conductivity [W/m·K]	U-value [W/m²·K]	SHGC [-]	Tvis [-]	μ [-]
Air gap (3 - 6 cm)	1.2	1005	0.33	-	-	-	-
Aluminium blinds	2800	880	160	-	-	-	1000000
Aluminium frame windows	2800	880	160	3.98	-	-	1000000
Bitumen	1100	100	0.24	-	-	-	50000
Cast concrete slab	2000	1000	1.13	-	-	-	70
Cement hollow bricks masonry	1210	1000	0.81	-	-	-	10
Cement mortar	1860	840	0.72	-	-	-	10
Cement screed	1200	840	0.41	-	-	-	10
Cement slabs	1860	840	0.72	-	-	-	10
Ceramic brick	1200	900	0.47	-	-	-	10
Ceramic floor tiles	2300	840	1.3	-	-	-	10000
Ceramic roof tiles - terracotta	1700	840	0.81	-	-	-	30
Double-glazing 4-12(arg)-4 mm	-	-	-	1.25	0.579	0.698	-
Double-glazing 6-4(air)-6 mm	-	-	-	3.09	0.71	0.781	-
EPS expanded polystyrene	15	1400	0.04	-	-	-	20
EPS expanded polystyrene (old)	15	1400	0.05	-	-	-	20
Exterior plaster / mortar adhesive			0.72	-	-	-	10
Gravel	1840	840	0.36	-	-	-	10000
Gypsum plaster	1200	1000	0.4	-	-	-	4
Gypsum Plasterboard	900	1000	0.25	-	-	-	4
Hallow slab / concrete	2100	840	1.75	-	-	-	80
Hardboard / particles	600	1700	0.13	-	-	-	20
Joists and terracotta slab	1841	586	0.8	-	-	-	10
Linoleum floor	1200	1400	0.17	-	-	-	800
Metallic profiles	7800	480	45	-	-	-	1000000
Mineral wool insulation	30	840	0.035	-	-	-	1
Oak lathing	700	2390	0.19	-	-	-	20
Prefabricated wooden balcony	1000	1300	1.18	-	-	-	20
PVC frame windows	1390	900	0.17	2.2	-	-	50000
Reinforced concrete (1-2 % Steel)	2400	1000	2.5	-	-	-	80
Rubble masonry	1600	1045	0.81	-	-	-	15
Single-Glazing 6 mm	-	-	-	5.82	0.819	0.881	-
Solid wood, air-dried, planed	900	2000	0.15	-	-	-	20
Synthetic plaster (perlite)	800	837	0.18	-	-	-	10
Synthetic plaster / reinforce. Mesh	800	837	0.18	-	-	-	10
Timber floor	650	1200	0.14	-	-	-	20
Triple-glazing 4-12(arg)-6-12(arg)-4	-	-	-	0.68	0.443	0.633	-
Vapour barrier (aluminium)	2800	880	160	-	-	-	1000000
Wood particle board	600	1700	0.14	-	-	-	20
Wooden frame windows	700	2390	0.19	1.8	-	-	20
Wooden roller shutter (pinewood)	419	2720	0.14	-	-	-	20
Wooden shutter (plywood)	700	1420	0.15	-	-	-	20
XPS extruded polystyrene	35	1400	0.034	-	-	-	100
Zinc	7200	390	113	-	-	-	1000000

Horizontal elements: Rse: 0.04 m²·K/W - Rsi: 0.10 m²·K/W

ρ – density, c - specific heat, λ - thermal conductivity, U - thermal transmittance, SHGC - solar heat gain coefficient, Tvis - visible transmittance coefficient, μ - water vapor diffusion resistance factor, Rse - exterior surface resistance, Rsi - interior surface resistance

Table 10-1. Main physical characteristics of materials used in the energy models. Values obtained from [**ISO 2007; LBNL 2017b, 2017c**].

10.1.2. Thermal bridge and condensation risk evaluation method

Thermal bridges

The standard SIA 380/1 **[SIA 2016a]** classifies the most relevant thermal bridges in a series of groups. The Swiss catalogue of thermal bridges **[Infomind Sàrl 2003]** uses this classification, adding different subgroups depending on the type of building façade (external insulation, wooden construction, interior insulation, double-wall masonry). An example of codification is presented in Table 10-2.

Group-type (openings / windows)
Subgroup-type (window sill)
Type of façade (external insulation)
Number (window frame, interior position)

5 . 2 – A 2

Group type	Thermal bridge type according to SIA 380/1: 1) Flat roofs and balconies slabs. 2) Floor slabs and interior walls. 3) Sloped roofs and façade basements. 4) Window frame widening and store / blinds boxes. 5) Outline of the windows. 6) Pillars / columns and ventilated façade anchorage systems.
Subgroup Type of façade	Subgroup depending on the observed component within the group type. A) External insulation systems (ETICS) and ventilated / façades. H) Wooden construction. I) Interior insulation. Z) Double-walled masonry.

Table 10-2. Codification of thermal bridges according to the Swiss catalogue **[Infomind Sàrl 2003]** and the standard SIA 380/1 [**SIA 2016a**].

From this catalogue, is it possible to obtain reference values for each type of LTB. It is important to highlight that depending on the constructive detail and the pre-existing elements of the building, the choice of certain values in the catalogue are approximate because the type of construction with which they have been calculated does not exactly match what we have in our scenarios. For this, a verification at critical junction points of the envelope is done in more detail, through the use of THERM [**LBNL 2017b**], a two-dimensional conduction heat-transfer analysis tool based on the finite-element method. The tool is configured based on the specifications of the standard SIA 180: 2014 [**SIA 2014**].

The objectives of this detailed calculation are first, to obtain a more precise value, better adapted to our case study, and second, to verify the risk of condensation (superficial and interstitial) and of long-term mould formation. We first proceed to a calculation of the value of the LTB using the formula below, through the evaluation of the heat flow (Φ) that crosses the discontinuity, considering an indoor air temperature (Ti) of 20°C and outdoor air temperature (Te) of 0°C.

$$\boldsymbol{\psi = [\Phi / Te - Ti] - U \cdot L}$$

Where

Ψ: Value of the linear thermal bridge **[W/m·K]**

Φ: Heat flow that crosses the section **[W]**

Te: Outdoor air temperature **[°C]**

Ti: Indoor air temperature [°**C]**

U: Thermal transmittance of the homogeneous part of the section **[W/m²·K]**

L: Length of the considered section **[m]**

The values of Φ and U have been calculated with THERM tool.

Condensation and mould risk

For the second part, it is important to check 1) the risk of interstitial condensation between the different layers of the homogenous part of the envelope, and 2) the superficial condensation risk and mould formation at the most critical points (which generally coincide with the location of thermal bridges).

The interstitial condensation occurs where the vapour pressure calculated is above the saturation vapour pressure. The check of this type of condensation risk is realised with the DesignBuilder software **[DesignBuilder 2018]**, through the Glaser method, according to the ISO standard 13788 **[ISO 2012]**.

For the risk of superficial condensation and mould formation on the internal face of the envelope, we proceed to a calculation of the Temperature factor (fRsi) using the formulas below.

It is necessary to consider two different boundary conditions in terms of minimum outdoor temperature (Te) at the surface of the studied detail. For the condensation risk study the minimum outdoor temperature (Ta,e,min) is used, and for the mould risk study the mean outdoor temperature (Ta,e,m). These values are given in the standard SIA 180:2014 **[SIA 2014]** for the city of Neuchâtel, corresponding to Ta,e,min=1.4 °C and Ta,e,m = 9.2 °C.

This standard also defines the limit values of the temperature factor (fRsi) for Neuchâtel: fRsi, min = 0.59 (for condensation analysis) and fRsi, min = 0.75 (for mould analysis).

In order to check if there is no risk of condensation or mould formation, each point examined in the thermal bridge study must comply with fRsi > fRsi, min. Otherwise, there is a high probability of condensation or mould formation.

For superficial condensation risk study:

fRsi, min = Tsi, min - Ta,e,min /Ti - Ta,e,min

For mould formation risk study:

fRsi, min = Tsi, min - Ta,e,m / Ti - Ta,e,m

Where

fRsi, min: Temperature factor [-]

Tsi, min: Minimum temperature of the internal surface [°**C]**

Ta,e,min: Minimum temperature of the external surface according to the location [°**C]**

Ta,e,m: Mean temperature of the external surface according to the location [°**C]**

Ti: Indoor air temperature [°**C]**

The values of Tsi, min have been calculated with the THERM tool.

10.1.3. Archetype 1

Materials description

Table 10-3 to Table 10-7 present the description of the layers composing the building envelope including their thermal / visual characteristics for each scenario for Archetype 1.

E0 – Current status		
Roof – *ref. Dsi01**		**U-1.59 W/m²·K**
a – Ceramic rood tiles and slats	8 cm	λ - 1.00 W/m·K
b - Hardboard	0.6 cm	λ – 0.13 W/m·K
c – Oak lathing	5 cm	λ – 0.19 W/m·K
d - Solid wood, air-dried, planed	1.5 cm	λ – 0.15 W/m·K
Façade – *ref. Ws01**		**U-1.07 W/m²·K**
a - Exterior plaster / mortar adhesive	2 cm	λ - 0.72 W/m·K
b - Rubble masonry	40 cm	λ - 0.81 W/m·K
c - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bsi07**		**U-0.94 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Hallow slab / concrete	20 cm	λ - 1.75 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-1.74 W/m²·K**
a – Ceramic floor tiles	2	λ – 1.30 W/m·K
b – Cement screed	7	λ - 0.41 W/m·K
c – Cast concrete slab	20	λ - 1.13 W/m·K
Solar protections		
Wooden shutter	3 cm	-
Balconies		
Cement slabs	12 cm	-
Metallic profiles	IPE 100	-
Openings **		**U-5.70 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Single-Glazing	6 mm	U-5.82 W/m²·K
Solar heat gain coefficient - SHGC	0.819	
Visible transmittance coefficient - Tvis	0.881	

Table 10-3. Composition of the different parts of the building envelope for scenario E0, Archetype 1. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S0 – Baseline		
Roof – *ref. Dsi01**		**U- 0.25 W/m²·K**
a – Ceramic roof tiles and slats	5 cm	λ - 1.00 W/m·K
b - Hardboard	0.6 cm	λ – 0.13 W/m·K
c – Oak lathing	5 cm	λ – 0.19 W/m·K
d – Mineral wool insulation	12 cm	λ – 0.035 W/m·K
e - Vapour barrier	-	-
f - Solid wood, air-dried, planed	1.5 cm	λ – 0.15 W/m·K
Façade – *ref. Ws01**		**U- 0.25 W/m²·K**
a - Synthetic plaster / reinforce. mesh	1 cm	λ - 0.18 W/m·K
b – XPS extruded polystyrene	12 cm	λ - 0.034 W/m·K
c - Exterior plaster / mortar adhesive	2 cm	λ - 0.72 W/m·K
d - Rubble masonry	40 cm	λ - 0.81 W/m·K
e - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bsi07**		**U- 0.30 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Hallow slab / concrete	20 cm	λ - 1.75 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-1.74 W/m²·K**
a – Ceramic floor tiles	2	λ – 1.30 W/m·K
b – Cement screed	7	λ - 0.41 W/m·K
c – Cast concrete slab	20	λ - 1.13 W/m·K
Solar protections		
Wooden shutter	3 cm	-
Balconies		
Cement slabs	12 cm	-
Metallic profiles	IPE 100	-
Openings **		**U- 1.30 W/m²·K**
PVC frame windows	-	U- 2.20 W/m²·K
Double-glazing (with argon gap)	4-12-4 mm	U- 1.25 W/m²·K
Solar heat gain coefficient - SHGC	0.579	
Visible transmittance coefficient - Tvis	0.698	

Table 10-4. Composition of the different parts of the building envelope for scenario S0, Archetype 1. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2016**]; ** Database WINDOW [**LBNL 2017a**] and DesignBuilder [**DesignBuilder 2018**].

S1 – BIPV Conservation

Roof – *ref. Dsi01**		**U- 0.20 W/m²·K**
a – Standard-size PV panels Megaslate® system	Terracotta coloured film	η - 14.5 % (STC)
b - Hardboard	0.6 cm	λ – 0.13 W/m·K
c – Oak lathing	5 cm	λ – 0.19 W/m·K
d – Mineral wool insulation	16 cm	λ – 0.035 W/m·K
e - Vapour barrier	-	-
f - Solid wood, air-dried, planed	1.5 cm	λ – 0.15 W/m·K
Façade – *ref. Ws01**		**U- 0.20 W/m²·K**
a - Synthetic plaster / reinforce. mesh	1 cm	λ - 0.18 W/m·K
b – XPS extruded polystyrene	14 cm	λ - 0.034 W/m·K
c - Exterior plaster / mortar adhesive	2 cm	λ - 0.72 W/m·K
d - Rubble masonry	40 cm	λ - 0.81 W/m·K
e - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bsi07**		**U- 0.30 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Hallow slab / concrete	20 cm	λ - 1.75 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-1.74 W/m²·K**
a – Ceramic floor tiles	2	λ – 1.30 W/m·K
b – Cement screed	7	λ - 0.41 W/m·K
c – Cast concrete slab	20	λ - 1.13 W/m·K
Solar protections		
Wooden shutter	3 cm	-
Balconies		
Cement slabs	12 cm	-
Metallic profiles	IPE 100	-
Openings **		**U- 0.77 W/m²·K**
Wooden frame windows	-	U- 1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U- 0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-5. Composition of the different parts of the building envelope for scenario S1, Archetype 1. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2009, 2016**]; ** Database WINDOW [**LBNL 2017a**] and DesignBuilder [**DesignBuilder 2018**].

S2 – BIPV Renovation		
Roof – *ref. Dsi01**		**U- 0.19 W/m²·K**
a – Standard-size PV panels Megaslate® system	Terracotta coloured film	η - 14.5 % (STC)
b - Hardboard	0.6 cm	λ – 0.13 W/m·K
c – Oak lathing	5 cm	λ – 0.19 W/m·K
d – Mineral wool insulation	18 cm	λ – 0.035 W/m·K
e - Vapour barrier	-	-
f - Solid wood, air-dried, planed	1.5 cm	λ – 0.15 W/m·K
Façade – *ref. Ws01**		**U- 0.19 W/m²·K**
a - Synthetic plaster / reinforce. mesh	1 cm	λ - 0.18 W/m·K
b – XPS extruded polystyrene	16 cm	λ - 0.034 W/m·K
c - Exterior plaster / mortar adhesive	2 cm	λ - 0.72 W/m·K
d - Rubble masonry	40 cm	λ - 0.81 W/m·K
e - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bsi07**		**U- 0.30 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Hallow slab / concrete	20 cm	λ - 1.75 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-1.74 W/m²·K**
a – Ceramic floor tiles	2	λ – 1.30 W/m·K
b – Cement screed	7	λ - 0.41 W/m·K
c – Cast concrete slab	20	λ - 1.13 W/m·K
Solar protections		
Wooden shutter	3 cm	-
Balconies		
Cement slabs	12 cm	-
Metallic profiles	IPE 100	-
Custom-size PV panels on railing	Matt blue coloured film	η - 13.5 % (STC)
Openings **		**U- 0.77 W/m²·K**
Wooden frame windows	-	U- 1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U- 0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-6. Composition of the different parts of the building envelope for scenario S2, Archetype 1. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S3 – BIPV Transformation		
Roof – *ref. Dsi01**		**U- 0.17 W/m²·K**
a – Standard-size PV panels Megaslate® system	Terracotta coloured film	η - 14.5 % (STC)
b - Hardboard	0.6 cm	λ – 0.13 W/m·K
c – Oak lathing	5 cm	λ – 0.19 W/m·K
d – Mineral wool insulation	18 cm	λ – 0.035 W/m·K
e - Vapour barrier	-	-
f - Solid wood, air-dried, planed	1.5 cm	λ – 0.15 W/m·K
Façade – *ref. Wsi02**		**U- 0.17 W/m²·K**
a - Custom-size PV panels Megaslate® system	Light grey coloured film	η - 11 % (STC)
Air gap	5 cm	
b – Wood particle board / Fermacell®	1.5 cm	λ - 0.14 W/m·K
c – EPS expanded polystyrene (100% recycled)	18 cm	λ - 0.04 W/m·K
b – Wood particle board	1.5 cm	λ - 0.14 W/m·K
d - Exterior plaster / mortar adhesive	2 cm	λ - 0.72 W/m·K
e - Rubble masonry	40 cm	λ - 0.81 W/m·K
f - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bsi07**		**U- 0.30 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Hallow slab / concrete	20 cm	λ - 1.75 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-1.74 W/m²·K**
a – Ceramic floor tiles	2	λ – 1.30 W/m·K
b – Cement screed	7	λ - 0.41 W/m·K
c – Cast concrete slab	20	λ - 1.13 W/m·K
Solar protections		
Aluminium blinds	10 cm	-
Balconies		
New concrete slab	15 cm	-
New metallic profiles	IPE 100	-
Custom-size PV panels on railing	Light grey coloured film	η - 11 % (STC)
Openings **		**U- 0.77 W/m²·K**
Wooden frame windows	-	U- 1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U- 0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-7. Composition of the different parts of the building envelope for scenario S3, Archetype 1. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2009, 2016**]; ** Database WINDOW [**LBNL 2017a**] and DesignBuilder [**DesignBuilder 2018**].

Thermal bridge analysis

Table 10-8 shows the possible range of values (min – max) for each type of LTB, considering the constructive details proposed for Archetype 1, using reference values from **[Infomind Sàrl 2003]**. From those ranges, a value is selected for each scenario, as shown in Table 10-9.

Type	Linear thermal bridge (LTB) description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	3.2-A1	-0.09 -0.03
TB2	Wall-Unheated ground floor	3.4-A2	-0.04 +0.19
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I2	+0.07 +0.15
TB6	Wall-Floor (Ext – balcony)	1.1-A1/A3	+0.69 +1.05
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-A1	+0.07 +0.12
TB9	Jamb at window or door	5.2-A1	+0.08 +0.17
TB10	Lintel above window or door	5.3-A1	+0.07 +0.20
TB11	Ventilated façade fixation	6.2-U1	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-8. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]**.

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	-0.04	-0.04	-0.04	-0.03
TB2	+0.12	+0.14	+0.14	+0.15
TB3	+0.14	+0.13	+0.13	+0.11
TB4	+0.12	+0.13	+0.13	+0.15
TB6	+1.05	+0.75	+0.69	+0.13
TB7	-	-	-	+0.25
TB8	+0.10	+0.09	+0.10	+0.10
TB9	+0.15	+0.11	+0.11	+0.12
TB10	+0.20	+0.16	+0.16	+0.16
TB11	-	-	-	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-9. Linear thermal bridges values corresponding to Archetype 1 according to **[Infomind Sàrl 2003]**.

As mentioned, the selection of some values in the catalogue remains approximate for our specific construction. For instance, in the case of the thermal bridge TB6, corresponding to the intersection between the forged of the balcony with the façade, option of continuous slab and exterior insulation (ref. 1.1-A1 in **[Infomind Sàrl 2003]**), the catalogue offers two possible façade options, ceramic brick or reinforced concrete. However, Archetype 1 has an existing façade made of stone. The error should not be very large when dealing with external insulation with thermal transmittance values between 0.17 and 0.20 $W/m^2{\cdot}K$. Nevertheless, as verification is done more in detail for the points needing special attention, shown in Figure 10-1. For the remaining points, since an external insulation solution is proposed for all scenarios (S0, S1, S2 and S3), these thermal bridges are easily solvable.

The two thermal bridges examined using the THERM software **[LBNL 2017b]** correspond to TB10 for the window lintel (Figure 10-2 and Figure 10-3) and TB6 for the junction of the façade with the fourth-floor balcony slab (Figure 10-4 and Figure 10-5). For this last element, for the scenario S3 the balcony slab is replaced by a new one integrating a solution that minimises the thermal bridge. Results show that different LTB could have a big influence in the thermal behaviour of the building envelope. In this case a reduction of the 56% of thermal loses could be achieved comparing E0-Current status. Table 10-10 presents a comparison between the values obtained directly form the Swiss catalogue and the values obtained from the detailed study. Figure 10-3 presents the condensation and mould formation risk analysis conducted according to SIA 180 **[SIA 2014]** for window lintel. It is important to highlight that in the E0-Current status scenario, there is a risk of mould formation near the window frame.

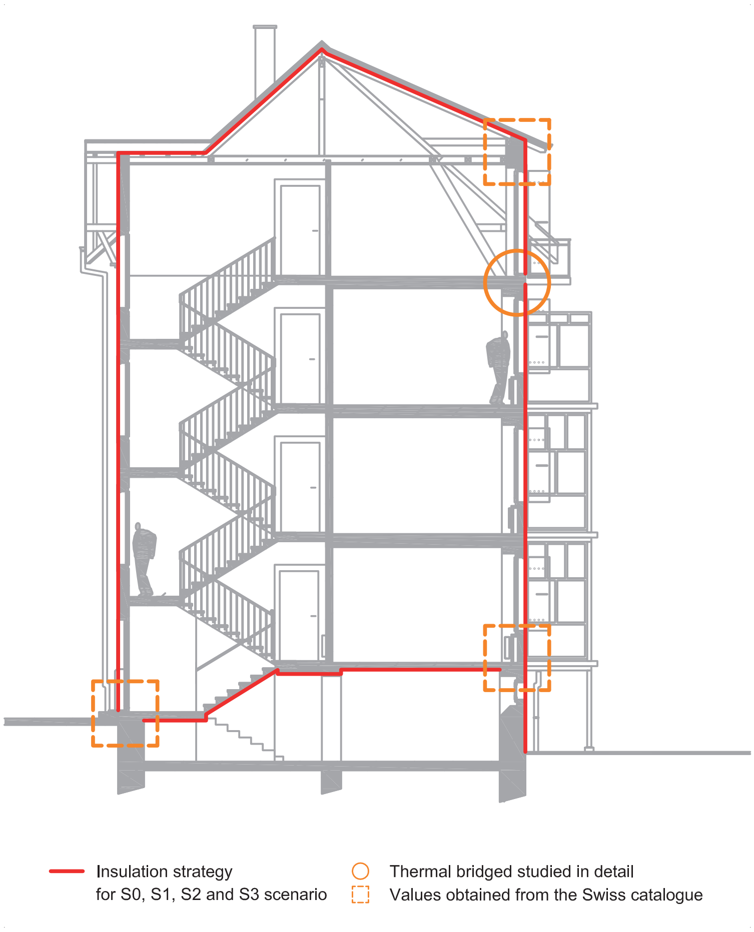


Figure 10-1. Insulation strategy and location of the main thermal bridges for the Archetype 1.

TB10 – Archetype 1	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
Values from catalogue	+0.20	+0.16	+0.16	+0.16
Values from THERM study	**+0.20**	**+0.18**	**+0.18**	**+0.17**

Table 10-10. Comparison between the thermal bridges values from the Swiss catalogue and the detailed study.

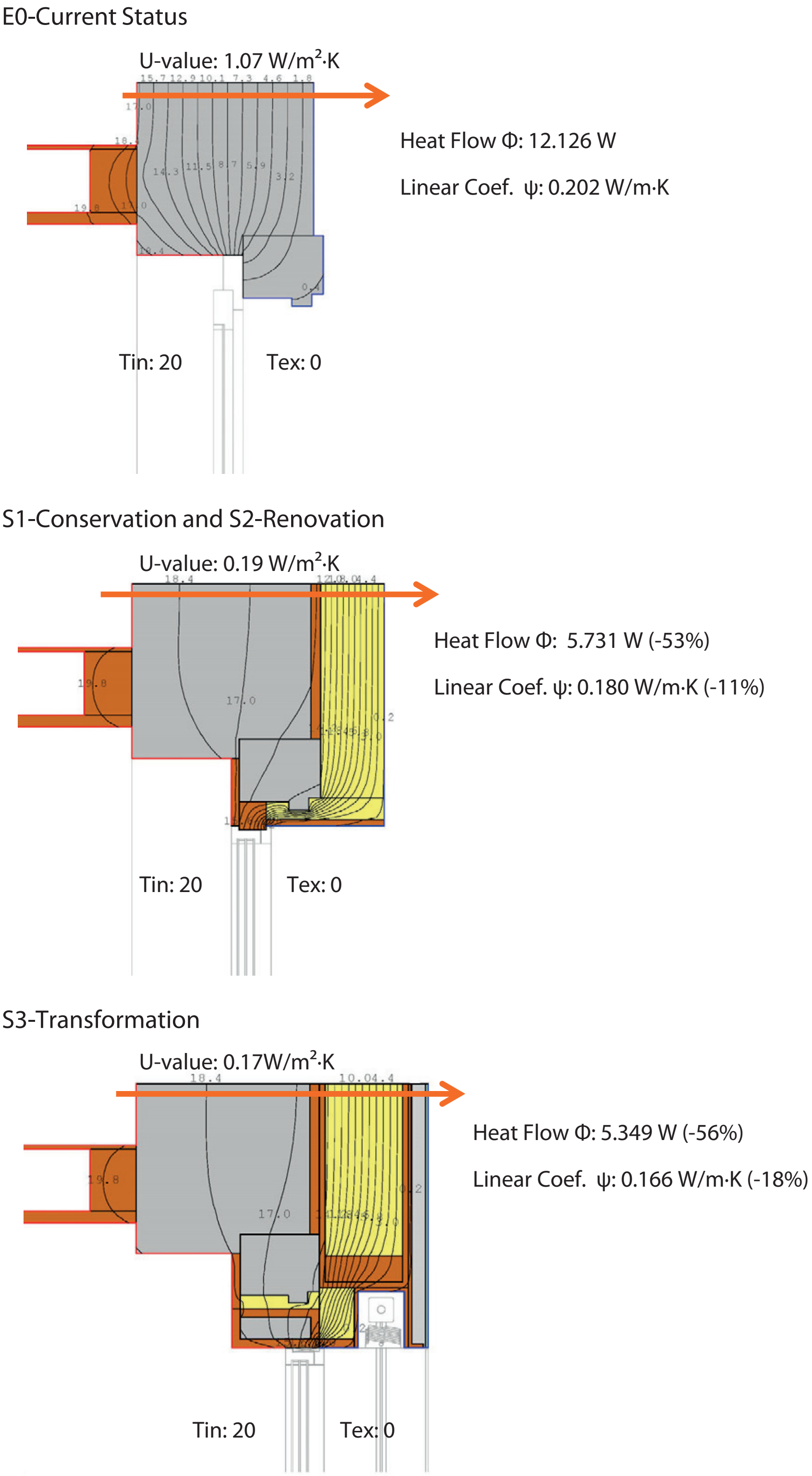


Figure 10-2. Window lintel thermal bridges analysis (TB10) for scenarios E0, S1, S2 and S3, for Archetype 1.

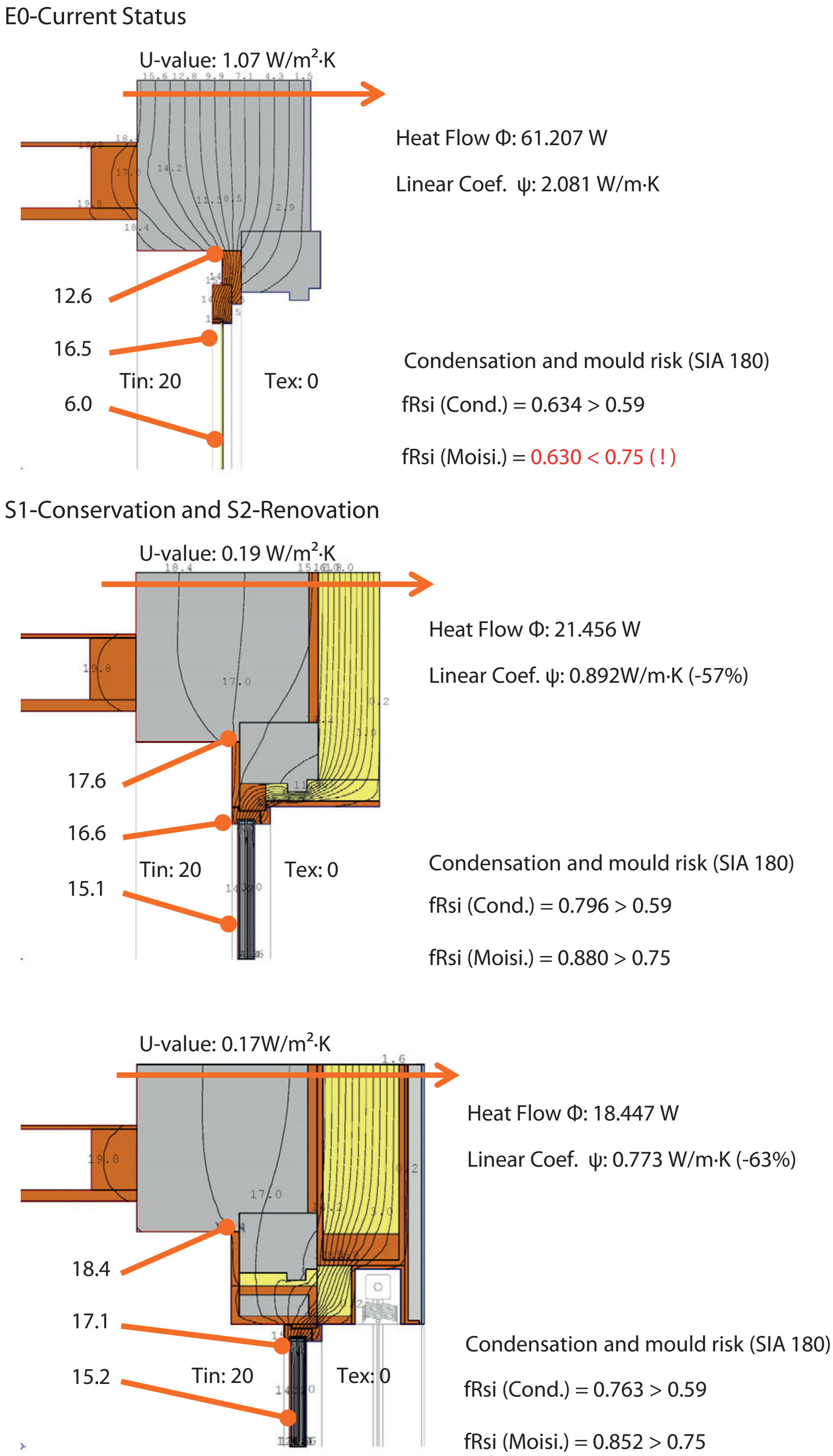


Figure 10-3. Window lintel condensation and mould analysis (TB10) for scenarios E0, S1, S2 and S3, for Archetype 1.

The LTB corresponding to the union between the façade and the balcony slab is tested for the two types of solution: (1) an External Thermal Insulation Composite System (ETICS) for S0, S1 and S2 scenarios, and (2) a prefabricated ventilated façade with substitution of the balcony using punctual fixation points for S3 scenario. Results are shown in Figure 10-4 (for LTB) and in Figure 10-5 (for the condensation analysis).

With the punctual anchorage system proposed in S3, the LTB is reduced with respect to the other scenarios and the current status. The obtained values (Table 10-11) are in accordance with the ranges shown in Table 10-8 from **[Infomind Sàrl 2003]**. The values obtained during the detailed analysis are lower than the values of the catalogue because in our case, the slab of the balcony is not the same as the floor slab (they are in contact but they are independent elements) so the heat flow is reduced.

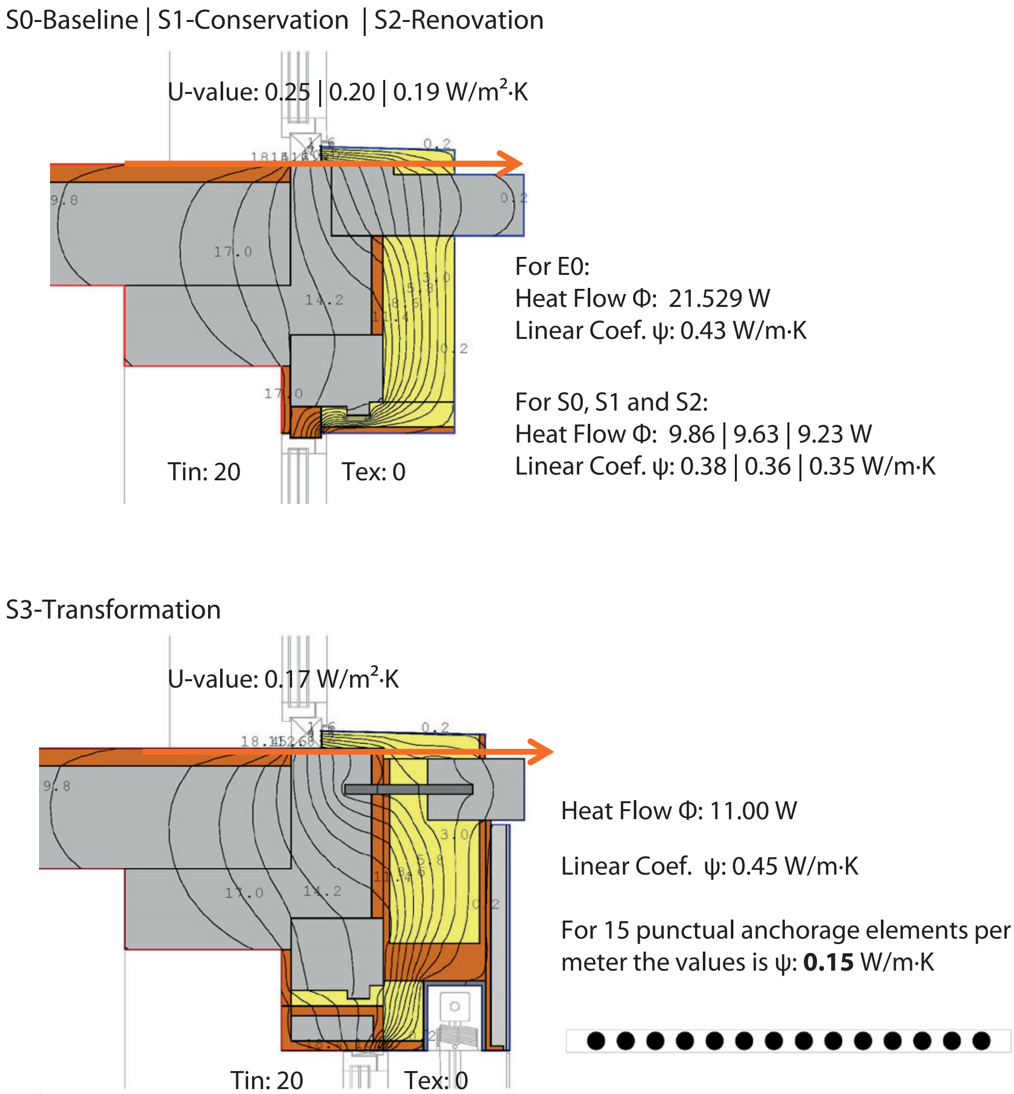
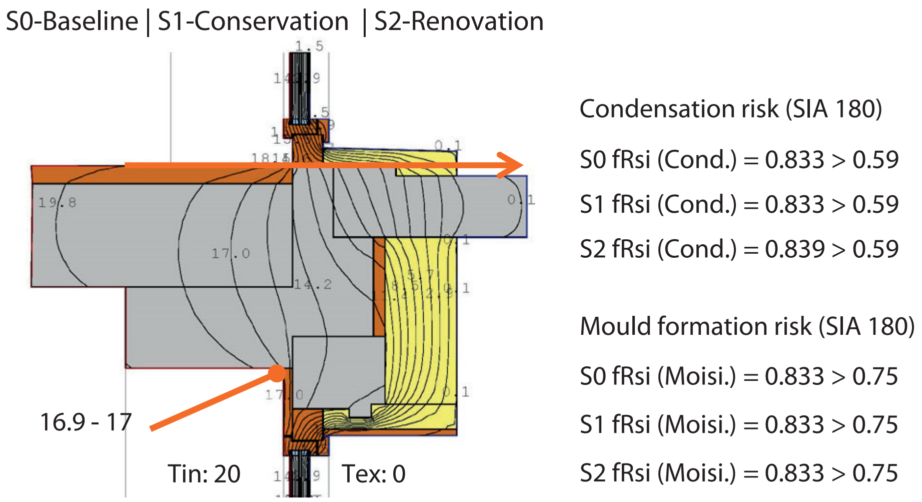


Figure 10-4. Wall-External floor (balcony) junction (TB6) analysis for scenarios S0 to S3, for Archetype 1.

TB6 – Archetype 1	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
Values from catalogue	+1.05	+0.75	+0.69	+0.13
Values from THERM study	**+0.43**	**+0.36**	**+0.35**	**+0.15**

Table 10-11. Comparison between the thermal bridges values from the Swiss catalogue and the detailed study.



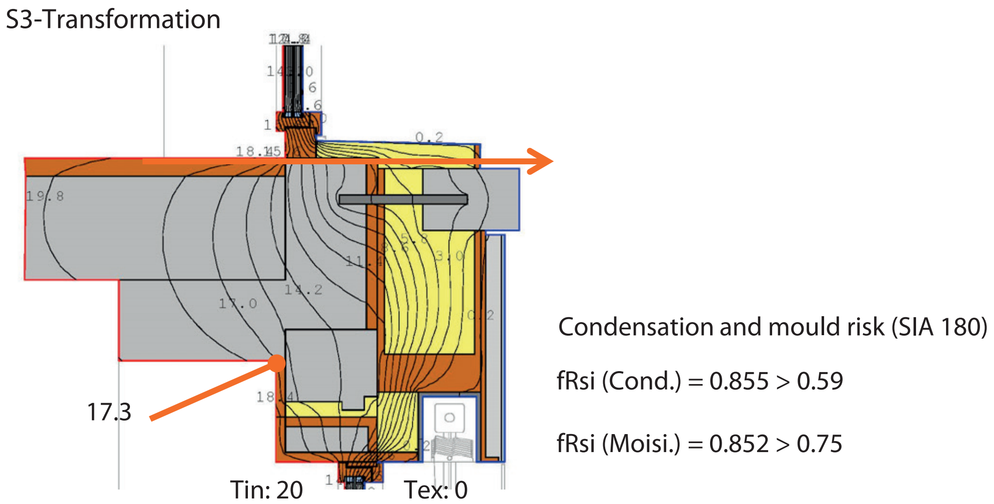


Figure 10-5. Wall-External floor (balcony) junction (TB6) analysis in terms of condensation and mould analysis for scenarios S2 and S3, for Archetype 1.

In terms of condensation risk, Figure 10-5 shows that no risk is observed in any scenario.

Table 10-12 lists the final values considered for the LTB for Archetype 1, which are used in the quantitative assessment (Chapter 7).

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	-0.04	-0.04	-0.04	-0.03
TB2	+0.12	+0.14	+0.14	+0.15
TB3	+0.14	+0.13	+0.13	+0.11
TB4	-	-	-	-
TB6	**+0.43**	**+0.36**	**+0.35**	**+0.15**
TB7	-	-	-	-
TB8	+0.10	+0.09	+0.10	+0.10
TB9	+0.15	+0.14	+0.14	+0.15
TB10	**+0.20**	**+0.18**	**+0.18**	**+0.17**
TB11	-	-	-	ΔU +0.03 W/m²·K

Values in **bold** have been calculated using the THERM software, other values are adopted from [Infomind Sàrl 2003].

Table 10-12. Linear thermal bridges values used for the Archetype 1.

Concerning the homogeneous part of the façade, an example of the resulting Glaser diagram is shown in Figure 10-6, allowing to verify and confirm that no risk of interstitial condensation exists between the different layers that form the envelope (for scenario S3). Indeed, in any point the calculated vapour pressure (in red) is above the saturation vapour pressure (in blue).

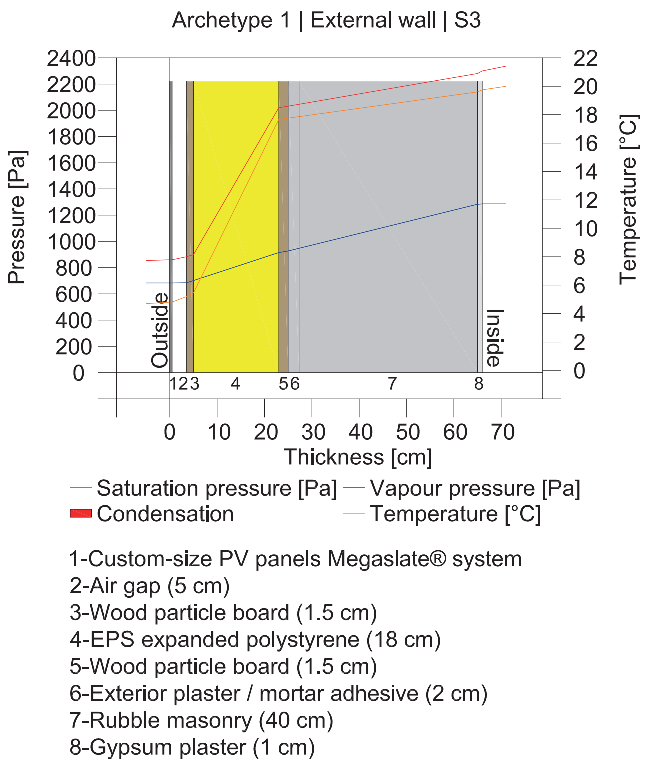
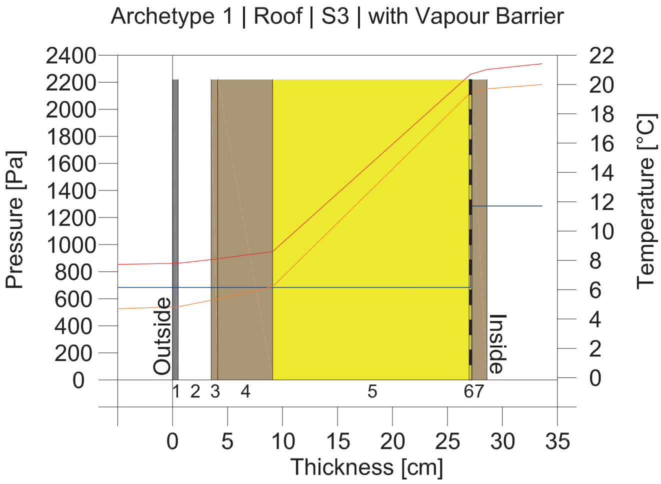


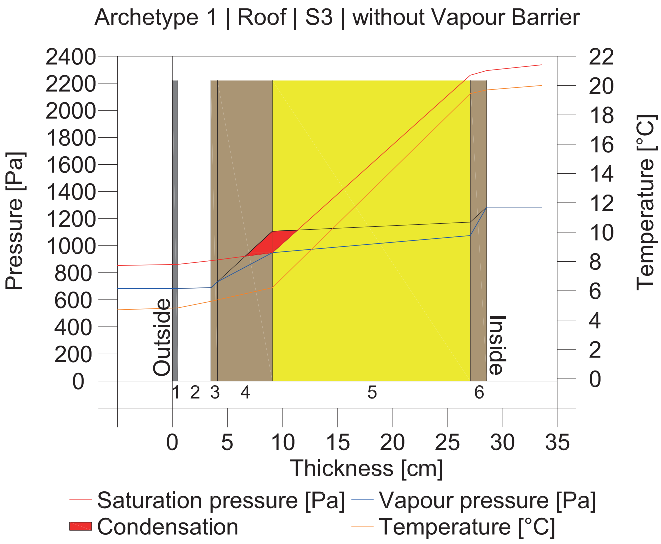
Figure 10-6. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario S3, Archetype 1.

An interesting case that shows the importance of these verifications is the insulation of the sloping roof. For this roof with a wooden structure, the insulation is placed below the existing tiles or photovoltaic panels (in the BIPV scenarios). The insulation is relatively close to the interior so it is important to have a layer that acts as a barrier to the diffusion of the vapour generated in the indoor environment, thus avoiding possible interstitial condensations in the hot face of the insulating layer.

A comparison between the use and absence of a vapour barrier is presented in Figure 10-7. In this case, an aluminium foil layer (not permeable) is enough to avoid the problem. Another option could be the use of extruded polystyrene (XPS) instead of stone wool as we propose, because the XPS is a closed cell insulation material with a high vapour resistivity of 600 MN·s/g·m, compared to 6 MN·s/g·m offered by the mineral wool insulation material [**ISO 2007**]. In any case it is recommended to verify the embodied energy of each option. The same should be considered in interior insulation solutions.



1-Standard-size PV panels Megaslate® system
2-Air gap (5 cm)
3-Hardboard (0.6 cm)
4-Oak lathing (5 cm)
5-Mineral wool insulation (18 cm)
6-Aluminium foil (vapour barrier)
7-Solid wood, air-dried, planed (1.5 cm)



1-Standard-size PV panels Megaslate® system
2-Air gap (5 cm)
3-Hardboard (0.6 cm)
4-Oak lathing (5 cm)
5-Mineral wool insulation (18 cm)
6-Solid wood, air-dried, planed (1.5 cm)

Figure 10-7. Glaser diagram for the roof envelope (S3 scenario) with vapour barrier (top) and without vapour barrier (bottom), Archetype 1.

10.1.4. Archetype 2

Materials description

Table 10-13 to Table 10-17 present the description of the layers composing the building envelope including their thermal / visual characteristics for each scenario for Archetype 2.

E0 – Current status		
Roof – *ref. Dsi01**		**U-0.93 W/m²·K**
a – Ceramic roof tiles and slats	8 cm	λ - 1.00 W/m·K
b - Hardboard	2.5 cm	λ – 0.13 W/m·K
c – Oak lathing	5 cm	λ - 0.19 W/m·K
d - Hardboard	2 .5 cm	λ – 0.13 W/m·K
Façade – *ref. Ws03**		**U-1.13 W/m²·K**
a - Exterior plaster	2 cm	λ - 0.72 W/m·K
b – Cement hollow bricks masonry	35 cm	λ - 0.81 W/m·K
c - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs06a**		**U-1.06 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b - Vapour barrier	-	-
c – Cement mortar	3 cm	λ - 0.72 W/m·K
d – Joists and terracotta slab	20 cm	λ – 0.80 W/m·K
e - Gypsum plaster	1 cm	λ - 0.40 W/m·K
External floor (ground) **–** *ref. Bs06a**		**1.63 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Cast concrete slab	15 cm	λ - 1.13 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Concrete slabs	18 cm	-
Openings **		**U-5.70 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Single-Glazing	6 mm	U-5.82 W/m²·K
Solar heat gain coefficient - SHGC	0.819	
Visible transmittance coefficient - Tvis	0.881	

Table 10-13. Composition of the different parts of the building envelope for scenario E0, Archetype 2. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S0 – Baseline		
Roof – *ref. Dsi01**		**U- 0.25 W/m²·K**
a - Ceramic roof tiles and slats	5 cm	λ - 1.00 W/m·K
b - Hardboard	2.5 cm	λ – 0.13 W/m·K
c – Mineral wool insulation	12 cm	λ – 0.035 W/m·K
d - Vapour barrier	-	-
e - Hardboard	2.5 cm	λ – 0.13 W/m·K
Façade – *ref. Ws03**		**U- 0.25 W/m²·K**
a - Exterior plaster	2 cm	λ - 0.72 W/m·K
b – Cement hollow bricks masonry	35 cm	λ - 0.81 W/m·K
c – XPS extruded polystyrene	8 cm	λ - 0.034 W/m·K
d – XPS extruded polystyrene	3 cm	λ - 0.034 W/m·K
e - Plasterboard	1.5 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs06a**		**U-0.29 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b - Vapour barrier	-	-
c – Cement mortar	3 cm	λ - 0.72 W/m·K
d – Joists and terracotta slab	20 cm	λ – 0.80 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) **–** *ref. Bs06a**		**1.63 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Cast concrete slab	15 cm	λ - 1.13 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Concrete slabs	18 cm	-
Openings **		**U- 1.30 W/m²·K**
PVC frame windows	-	U- 2.20 W/m²·K
Double-glazing (with argon gap)	4-12-4 mm	U- 1.25 W/m²·K
Solar heat gain coefficient - SHGC	0.579	
Visible transmittance coefficient - Tvis	0.698	

Table 10-14. Composition of the different parts of the building envelope for scenario S0, Archetype 2. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2016**]; ** Database WINDOW [**LBNL 2017a**] and DesignBuilder [**DesignBuilder 2018**].

S1 – BIPV Conservation		
Roof – *ref. Dsi01**		**U- 0.20 W/m²·K**
a – Standard-size PV panels Megaslate® system	Terracotta coloured film	η - 14.5 % (STC)
b - Hardboard	2.5 cm	λ – 0.13 W/m·K
c – Mineral wool insulation	15 cm	λ – 0.035 W/m·K
d - Vapour barrier	-	-
e - Hardboard	2.5 cm	λ – 0.13 W/m·K
Façade – *ref. Ws03**		**U- 0.20 W/m²·K**
a - Exterior plaster	2 cm	λ - 0.72 W/m·K
b – Cement hollow bricks masonry	35 cm	λ - 0.81 W/m·K
c – XPS extruded polystyrene	8 cm	λ - 0.034 W/m·K
d – XPS extruded polystyrene	6 cm	λ - 0.034 W/m·K
e - Plasterboard	1.5 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs06a**		**U-0.29 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b - Vapour barrier	-	-
c – Cement mortar	3 cm	λ - 0.72 W/m·K
d – Joists and terracotta slab	20 cm	λ – 0.80 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) **–** *ref. Bs06a**		**1.63 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Cast concrete slab	15 cm	λ - 1.13 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Concrete slabs	18 cm	-
Openings **		**U- 0.77 W/m²·K**
Wooden frame windows	-	U- 1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U- 0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-15. Composition of the different parts of the building envelope for scenario S1, Archetype 2. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2009, 2016**]; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S2 – BIPV Renovation		
Roof – *ref. Dsi01**		**U- 0.19 W/m²·K**
a – Standard-size PV panels Megaslate® system	Terracotta coloured film	η - 14.5 % (STC)
b - Hardboard	2.5 cm	λ - 0.13 W/m·K
c – Mineral wool insulation	16 cm	λ – 0.035 W/m·K
d - Vapour barrier	-	-
e - Hardboard	2.5 cm	λ – 0.13 W/m·K
Façade – *ref. Ws01**		**U- 0.19 W/m²·K**
a - Synthetic plaster / reinforce. mesh	1 cm	λ - 0.18 W/m·K
b – XPS extruded polystyrene	15 cm	λ - 0.034 W/m·K
a - Exterior plaster	2 cm	λ - 0.72 W/m·K
b – Cement hollow bricks masonry	35 cm	λ - 0.81 W/m·K
c - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs06a**		**U-0.29 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b - Vapour barrier	-	-
c – Cement mortar	3 cm	λ - 0.72 W/m·K
d – Joists and terracotta slab	20 cm	λ – 0.80 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs06a**		**1.63 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Cast concrete slab	15 cm	λ - 1.13 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Concrete slabs	18 cm	-
Openings **		**U- 0.77 W/m²·K**
Wooden frame windows	-	U- 1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U- 0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-16. Composition of the different parts of the building envelope for scenario S2, Archetype 2. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S3 – BIPV Transformation		
Roof – *ref. Dsi01**		**U- 0.17 W/m²·K**
a – Standard-size PV panels Megaslate® system	Terracotta coloured film	η - 14.5 % (STC)
b - Hardboard	2.5 cm	λ - 0.13 W/m·K
c – Mineral wool insulation	20 cm	λ – 0.035 W/m·K
d - Vapour barrier	-	-
e - Hardboard	2.5 cm	λ – 0.13 W/m·K
Façade – *ref. Wsi02**		**U- 0.17 W/m²·K**
a - Custom-size PV panels Megaslate® system	Light grey coloured film	η - 11 % (STC)
Air gap	5 cm	
b – Wood particle board / Fermacell®	1.5 cm	λ - 0.14 W/m·K
c – EPS expanded polystyrene (100% recycled)	16 cm	λ - 0.04 W/m·K
b – Wood particle board	1.5 cm	λ - 0.14 W/m·K
a - Exterior plaster	2 cm	λ - 0.72 W/m·K
b – Cement hollow bricks masonry	35 cm	λ - 0.81 W/m·K
c - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs06a**		**U-0.29 W/m²·K**
a – Timber floor	5 cm	λ - 0.14 W/m·K
b - Vapour barrier	-	-
c – Cement mortar	3 cm	λ - 0.72 W/m·K
d – Joists and terracotta slab	20 cm	λ – 0.80 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) **–** *ref. Bs06a**		**1.63 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c – Cement mortar	3 cm	λ - 0.72 W/m·K
c – Cast concrete slab	15 cm	λ - 1.13 W/m·K
Solar protections		
Aluminium blinds	10 cm	-
Balconies		
Prefabricated wooden balcony	15 cm	-
Openings **		**U- 0.77 W/m²·K**
Wooden frame windows	-	U- 1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U- 0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-17. Composition of the different parts of the building envelope for scenario S3, Archetype 2. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

Thermal bridge analysis

Table 10-18 and Table 10-19 show the possible range of values (min – max) for each type of LTB, considering the constructive details proposed for Archetype 2, using reference values from **[Infomind Sàrl 2003]**. From those ranges, a value is selected for each scenario, as shown in Table 10-20.

Type	Linear thermal bridge description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	3.2-I1	-0.16 -0.07
TB2	Wall-Unheated ground floor	3.4-I2	-0.16 +0.01
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I2	+0.07 +0.15
TB6	Wall-Floor (Ext – balcony)	1.1-I1	+0.69 +1.05
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-I3	+0.11 +0.17
TB9	Jamb at window or door	5.2-I1	+0.06 +0.11
TB10	Lintel above window or door	5.3-I4	+0.14 +0.19

Table 10-18. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]** for scenarios S0 and S1 (façade with internal insulation).

Type	Linear thermal bridge description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Roof-Wall	3.2-A1	-0.09 -0.03
TB2	Wall-Unheated ground floor	3.4-A2	-0.04 +0.19
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I2	+0.07 +0.15
TB6	Wall-Floor (Ext – balcony)	1.1-A1/A3	+0.69 +1.05
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-A1	+0.07 +0.12
TB9	Jamb at window or door	5.2-A1	+0.08 +0.17
TB10	Lintel above window or door	5.3-A1	+0.07 +0.20
TB11	Ventilated façade fixation	6.2-U1	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-19. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]** for scenarios S2 and S3 (façade with external insulation).

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	-0.09	-0.07	-0.04	-0.03
TB2	-0.04	+0.01	+0.14	+0.15
TB3	+0.14	+0.13	+0.13	+0.11
TB4	+0.12	+0.13	+0.13	+0.15
TB6	+0.70	+0.68	+0.69	+0.13
TB7	+0.22	+0.23	+0.25	+0.25
TB8	+0.15	+0.15	+0.14	+0.15
TB9	+0.06	+0.08	+0.11	+0.12
TB10	+0.18	+0.17	+0.16	+0.16
TB11	-	-	-	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-20. Linear thermal bridges values corresponding to Archetype 2 according to **[Infomind Sàrl 2003]**.

Differences between the catalogue options and our case study concern thermal bridge TB6, corresponding to the intersection between the forged of the balcony with the façade, option of continuous slab and exterior insulation (1.1-A1 according to the Swiss catalogue). The catalogue offers two possible façade options, ceramic brick or reinforced concrete, but Archetype 2 has an existing façade made of cement hollow bricks masonry.

The main thermal bridges and those needing special attention are identified in Figure 10-8 and Figure 10-9 and correspond to a TB10 for the window lintel (Figure 10-10, Figure 10-11) and TB6 for the junction of the façade with the fourth-floor balcony slab (Figure 10-12). For this last element, for the scenario S3 the balcony slab is replaced by a new one integrating a solution that minimises the thermal bridge.

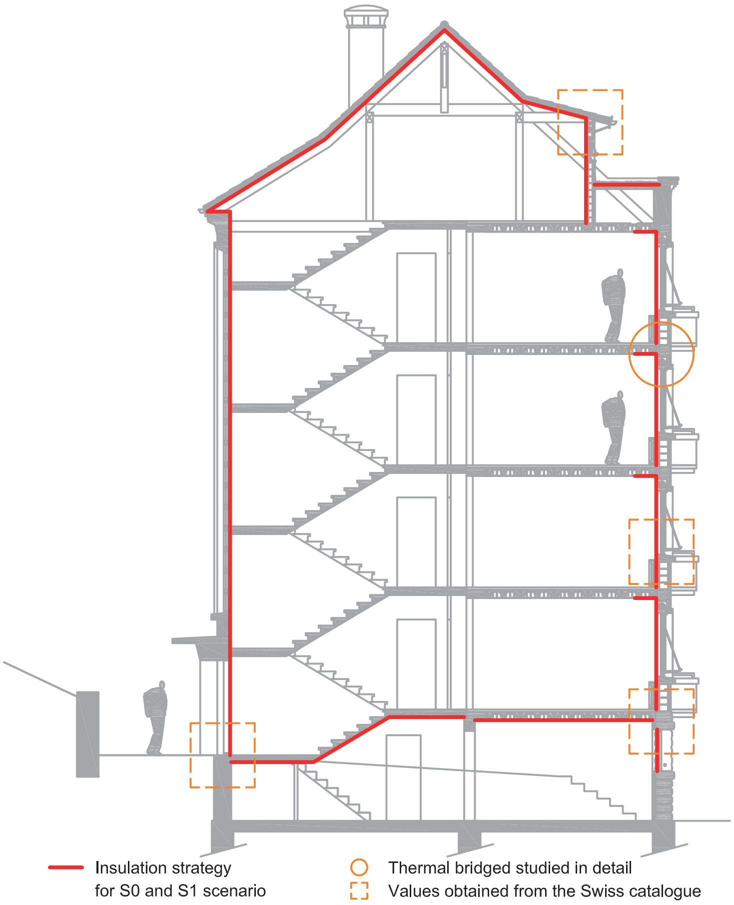


Figure 10-8. Insulation strategy and location of the main thermal bridges for the Archetype 2 (scenarios S0 and S1).

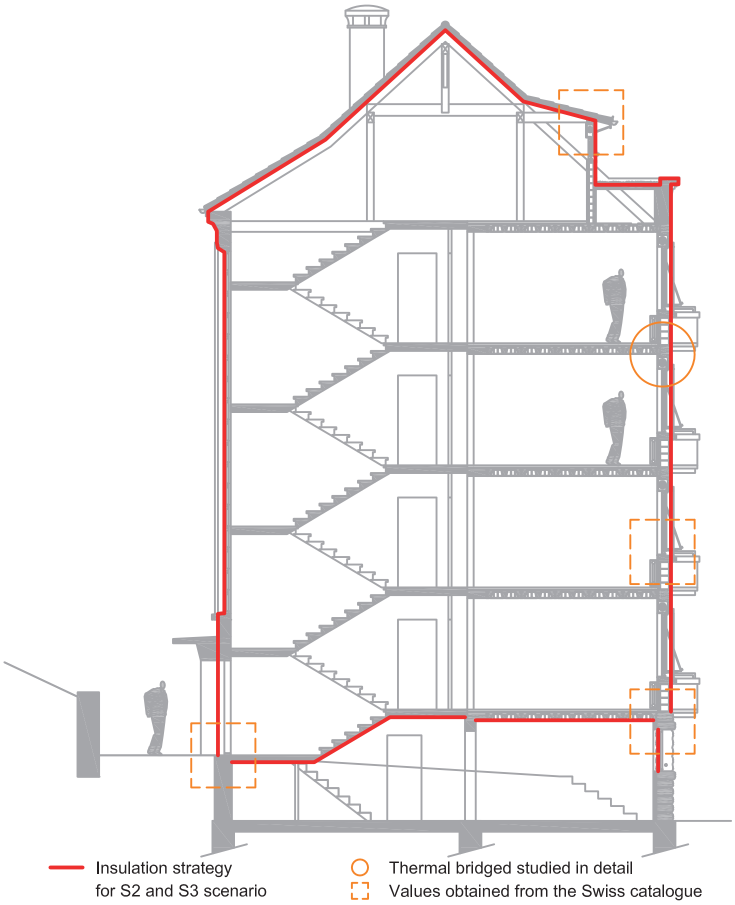


Figure 10-9. Insulation strategy and location of the main thermal bridges for the Archetype 2 (scenarios S2 and S3).

For the window lintel, results show that a reduction of the 89% in the thermal losses could be achieved in S3 compared to E0. Table 10-21shows the values obtained directly form the Swiss catalogue and from the detailed study. Except for scenario S3, the values are quite different.

Given the relatively old age of the building, and because the LTB provided by the Swiss catalogue correspond to more recent construction techniques, the THERM study values are used to conduct the energy simulation.

TB10 – Archetype 2	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
Values from catalogue	+0.20	+0.16	+0.16	+0.16
Values from THERM study	**+0.80**	**+0.80**	**+0.88**	**+0.18**

Table 10-21. Comparison between the thermal bridges values from the Swiss catalogue and the detailed study.

Figure 10-11 shows that, in the E0-Current status scenario, both a condensation and mould formation risk exist near the windows frame.

In the case of the union between the façade and the balcony slab (TB6, Figure 10-12), the thermal bridge is tested for scenarios S1, S2 and S3. For S1 and S2, the balconies are maintained and for S3, it is substituted using punctual fixation points. This punctual anchorage system allows reducing the LTB drastically. The obtained values (Table 10-23) are higher than the values expressed in the catalogue due to the discrepancies between the construction techniques used to generate the catalogue and those for this archetype from 1938.

TB6 – Archetype 2	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
Values from catalogue	+0.70	+0.68	+0.69	+0.13
Values from THERM study	**+1.23**	**+1.23**	**+0.94**	**+0.44**

Table 10-22. Comparison between the thermal bridges values from the Swiss catalogue and the detailed study.

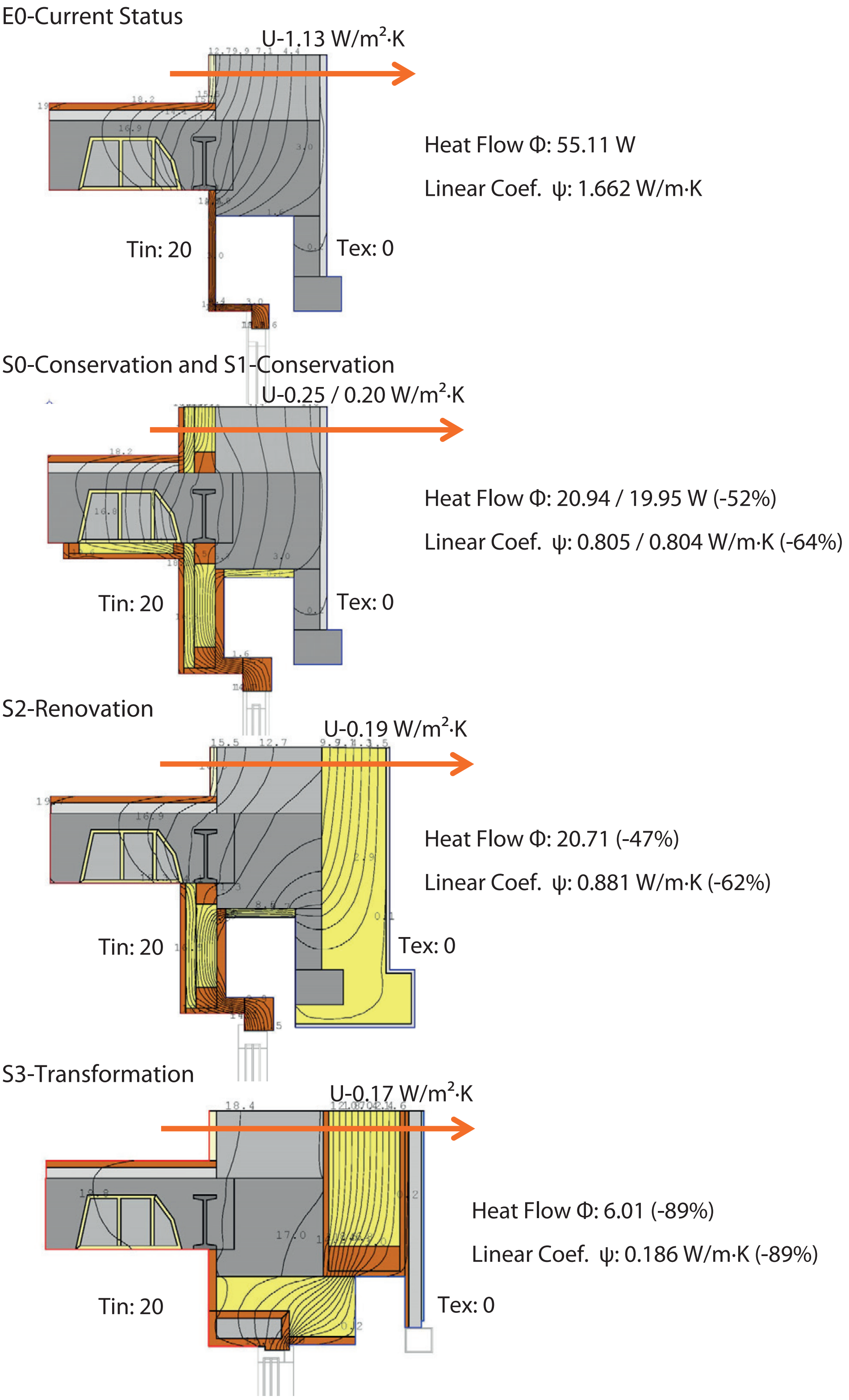


Figure 10-10. Window lintel thermal bridges analysis (TB10) for scenarios E0 to S3, for Archetype 2.

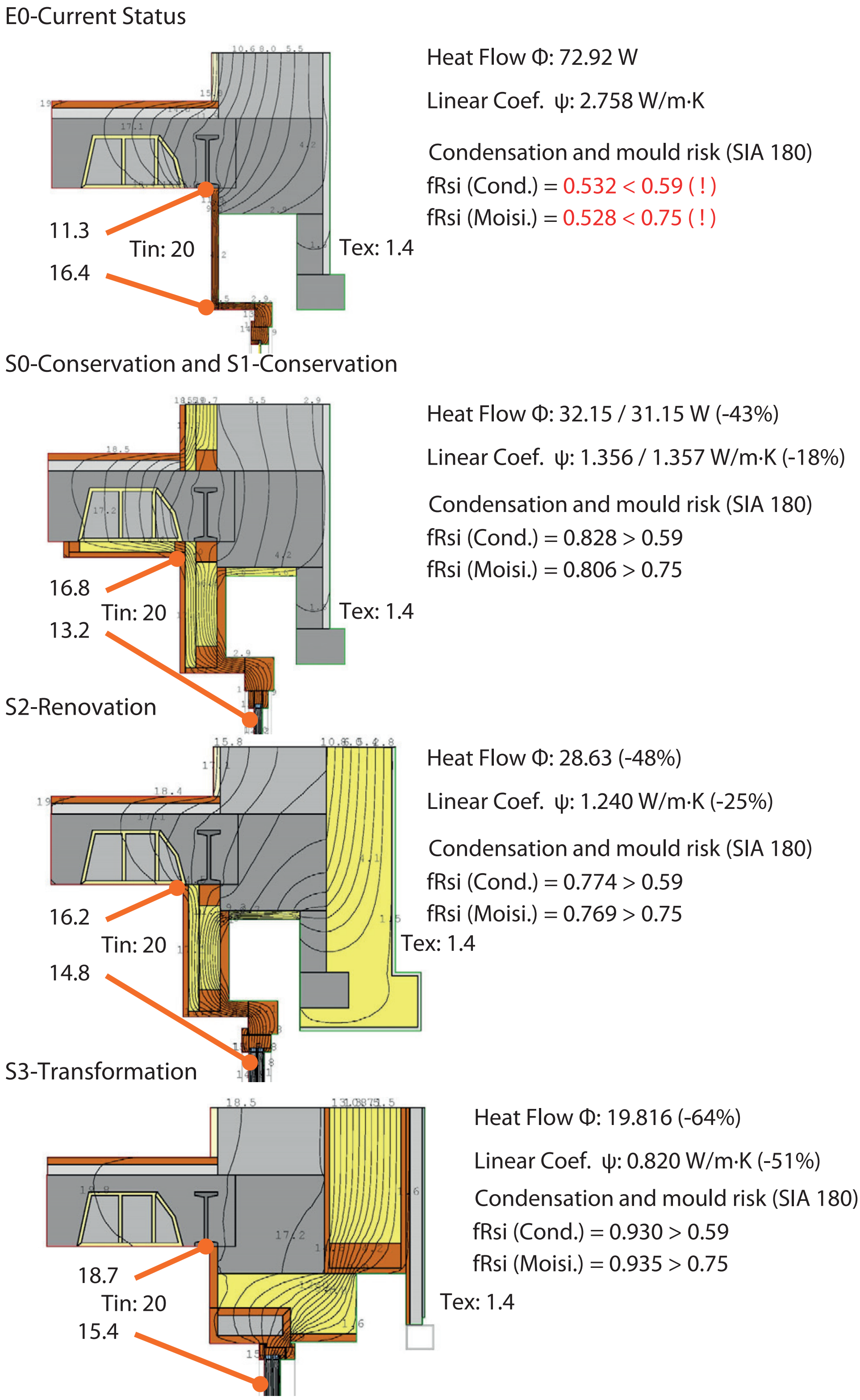


Figure 10-11. Window lintel condensation and mould analysis (TB10) for scenarios E0 to S3, for Archetype 2.

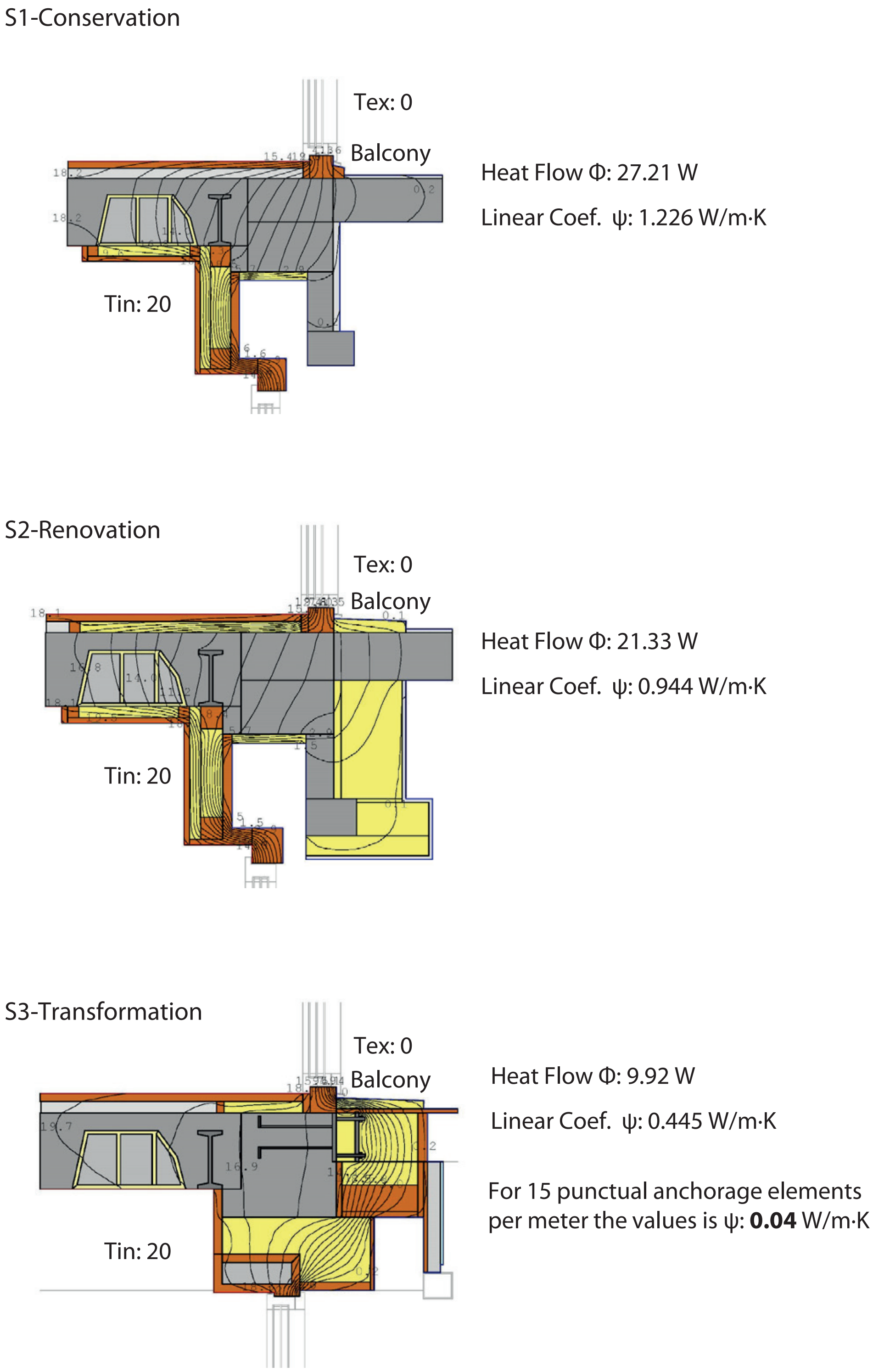


Figure 10-12. Wall-External floor (balcony) junction (TB6) analysis for scenarios S1, S2 and S3, for Archetype 2.

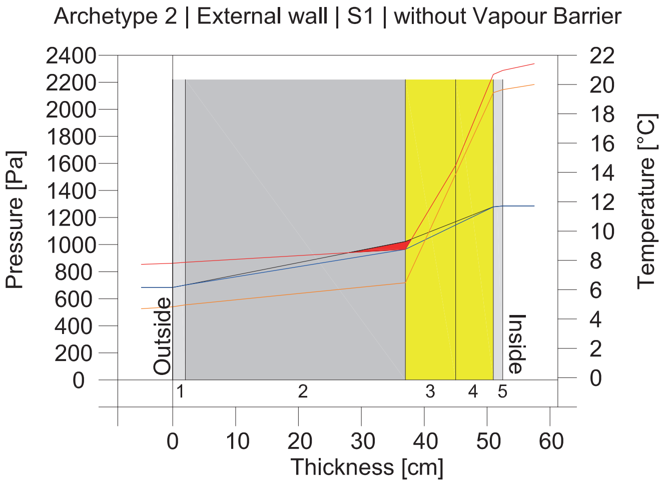
Table 10-23 lists the final values considered for LTB for Archetype 2, used to configure the energy simulation model of each scenario.

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	-0.09	-0.07	-0.04	-0.03
TB2	-0.04	+0.01	+0.14	+0.15
TB3	+0.14	+0.13	+0.13	+0.11
TB4	+0.12	+0.13	+0.13	+0.15
TB6	**+1.23**	**+1.23**	**+0.94**	**+0.44**
TB7	+0.22	+0.23	+0.25	+0.25
TB8	+0.15	+0.15	+0.14	+0.15
TB9	+0.06	+0.08	+0.11	+0.12
TB10	**+0.80**	**+0.80**	**+0.88**	**+0.18**
TB11	-	-	-	ΔU +0.03 $W/m^2 \cdot K$
Values in **bold** have been calculated using the THERM software, other values are adopted from [Infomind Sàrl 2003].				

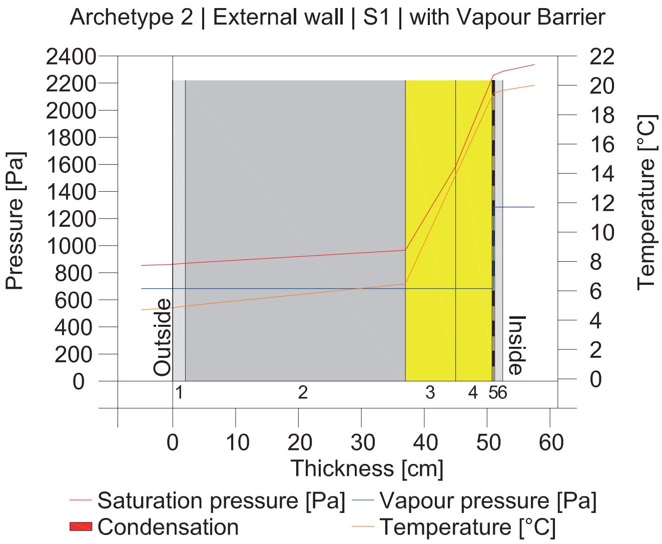
Table 10-23. Linear thermal bridges values used for the Archetype 2..

For S0 and S1 for which an interior insulation system is adopted, it is important to have a layer that acts as a barrier to the diffusion of the vapour generated in the indoor environment, as seen in the Glaser diagram shown in Figure 10-13 for S1. In this case an aluminium foil layer (not permeable) is enough to avoid the problem.

To complete this case study, the Glaser diagrams in Figure 10-14 and Figure 10-15 illustrate that no risk of interstitial condensation occurs in the façade composition for both scenarios S2 and S3, as at any point the calculated vapour pressure (in red) is above the saturation vapour pressure (in blue).

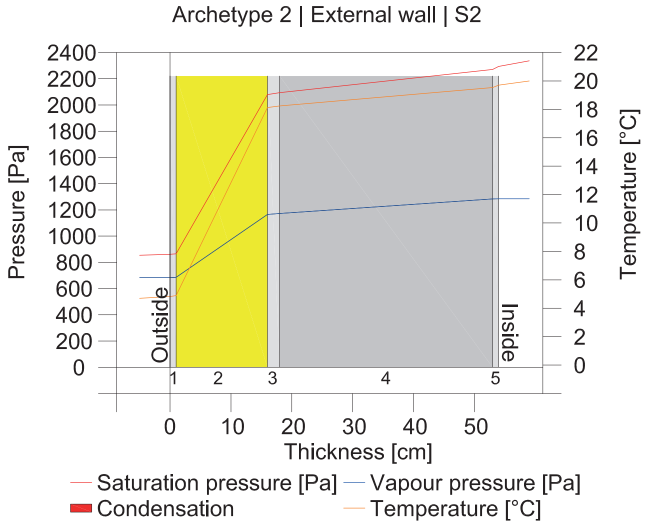


1-Exterior plaster (2 cm)
2-Cement hollow bricks masonry (35 cm)
3-EPS expanded polystyrene (8 cm)
4-EPS expanded polystyrene (6 cm)
5-Plasterboard (1.5 cm)



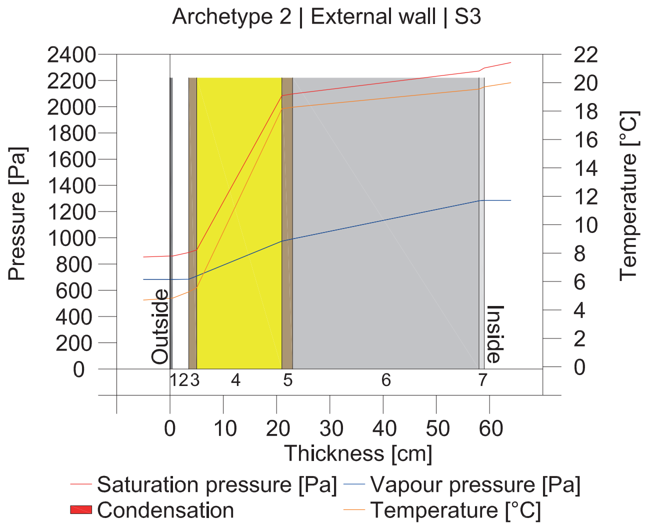
1-Exterior plaster (2 cm)
2-Cement hollow bricks masonry (35 cm)
3-EPS expanded polystyrene (8 cm)
4-EPS expanded polystyrene (6 cm)
5-Aluminium foil (vapour barrier)
6-Plasterboard (1.5 cm)

Figure 10-13. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario S1-Constervation, without vapour barrier (top) and with vapour barrier (bottom), Archetype 2.



1-Synthetic plaster / reinforced mesh (1 cm)
2-XPS extruded polystyrene (15 cm)
3-Exterior plaster / mortar adhesive (2 cm)
4-Cement hollow bricks masonry (35 cm)
5-Gypsum plaster (1 cm)

Figure 10-14. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario S2-Renovation, without vapour barrier (top) and with vapour barrier (bottom), Archetype 2.



1-Custom-size PV panels Megaslate® system
2-Air gap (5 cm)
3-Wood particle board (1.5 cm)
4-EPS expanded polystyrene (16 cm)
5-Wood particle board (1.5 cm)
6-Cement hollow bricks masonry (35 cm)
7-Gypsum plaster (1 cm)

Figure 10-15. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario S3-Transformation, without vapour barrier (top) and with vapour barrier (bottom), Archetype 2.

10.1.5. Archetype 3

Materials description

Table 10-24 to Table 10-28 present the description of the layers composing the building envelope including their thermal / visual characteristics for each scenario for Archetype 3.

E0 – Current status		
Roof – *ref. Ds02**		**U-0.91 W/m²·K**
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
c – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
d - Bitumen	0.4 cm	λ – 0.24 W/m·K
e - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
Façade – *ref. Ws11**		**U-1.18 W/m²·K**
a - Exterior plaster	2 cm	λ - 0.87 W/m·K
b – Ceramic brick	15 cm	λ - 0.47 W/m·K
c – Air gap	6 cm	
d – Ceramic brick	6 cm	λ - 0.47 W/m·K
e - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-1.93 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
e - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-0.60 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ - 2.50 W/m·K
d – XPS extruded polystyrene	4 cm	λ - 0.04 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Reinforced concrete slabs	20 cm	-
Openings **		**U-5.70 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Single-Glazing	6 mm	U-5.82 W/m²·K
Solar heat gain coefficient - SHGC	0.819	
Visible transmittance coefficient - Tvis	0.881	

Table 10-24. Composition of the different parts of the building envelope for scenario E0, Archetype 3. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2009, 2016**]; ** Database WINDOW [**LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S0 – Baseline		
Roof – *ref. Ds02**		**U-0.25 W/m²·K**
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
d – EPS expanded polystyrene	15 cm	λ - 0.04 W/m·K
d - Bitumen	0.4 cm	λ – 0.24 W/m·K
e - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
Façade – *ref. Ws11**		**U-0.25 W/m²·K**
a - Synthetic plaster / reinforce. mesh	1 cm	λ - 0.18 W/m·K
b – XPS extruded polystyrene	12 cm	λ - 0.034 W/m·K
b – Ceramic brick	15 cm	λ - 0.47 W/m·K
c – Air gap	6 cm	
d – Ceramic brick	6 cm	λ - 0.47 W/m·K
e - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-0.60 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ - 2.50 W/m·K
d – XPS extruded polystyrene	4 cm	λ - 0.04 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Reinforced concrete slabs	20 cm	-
Openings **		**U-1.30 W/m²·K**
PVC frame windows	-	U-2.20 W/m²·K
Double-glazing (with argon gap)	4-12-4 mm	U-1.25 W/m²·K
Solar heat gain coefficient - SHGC	0.579	
Visible transmittance coefficient - Tvis	0.698	

Table 10-25. Composition of the different parts of the building envelope for scenario S0, Archetype 3. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S1 – BIPV Conservation

Roof – *ref. Ds02**		**U-0.20 W/m²·K**
Standard-size PV panels	South	η - 20 % (STC)
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
d – EPS expanded polystyrene	18 cm	λ - 0.04 W/m·K
d - Bitumen	0.4 cm	λ – 0.24 W/m·K
e - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
Façade – *ref. Ws11**		**U-0.20 W/m²·K**
Additional layer with BIPV elements on the opaque part between windows:		
a - Custom-size PV panels Megaslate® system	Dark grey coloured film	η - 13 % (STC)
b - Air gap	5 cm	
The rest of the façade:		
a - Synthetic plaster / reinforce. mesh	1 cm	λ - 0.18 W/m·K
b – XPS extruded polystyrene	16 cm	λ - 0.034 W/m·K
b – Ceramic brick	15 cm	λ - 0.47 W/m·K
c – Air gap	6 cm	
d – Ceramic brick	6 cm	λ - 0.47 W/m·K
e - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-0.60 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ - 2.50 W/m·K
d – XPS extruded polystyrene	4 cm	λ - 0.04 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Reinforced concrete slabs	20 cm	-
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-26. Composition of the different parts of the building envelope for scenario S1, Archetype 3. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S2 – BIPV Renovation

Roof – *ref. Ds02**		**U-0.190 W/m²·K**
Standard-size PV panels	South	η - 20 % (STC)
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
d – EPS expanded polystyrene	20 cm	λ - 0.04 W/m·K
d - Bitumen	0.4 cm	λ – 0.24 W/m·K
e - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
Façade – *ref. Ws11**		**U-0.19 W/m²·K**
External layer with BIPV elements on the opaque part between windows:		
a - Custom-size PV panels Megaslate® system	Dark grey coloured film	η - 13 % (STC)
b - Air gap	5 cm	
The rest of the façade:		
a - Custom-size PV panels Megaslate® system	Light grey coloured film	η - 11 % (STC)
b - Air gap	5 cm	
d – XPS extruded polystyrene	15 cm	λ - 0.034 W/m·K
e – Ceramic brick	15 cm	λ - 0.47 W/m·K
f – Air gap	6 cm	
g – Ceramic brick	6 cm	λ - 0.47 W/m·K
h - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-0.60 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ - 2.50 W/m·K
d – XPS extruded polystyrene	4 cm	λ - 0.04 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Reinforced concrete slabs	20 cm	-
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-27. Composition of the different parts of the building envelope for scenario S2, Archetype 3. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S3 – BIPV Transformation		
Roof – *ref. Ds02**		**U-0.170 W/m²·K**
Standard-size PV panels	South	η - 20 % (STC)
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
d – EPS expanded polystyrene	22 cm	λ - 0.04 W/m·K
d - Bitumen	0.4 cm	λ – 0.24 W/m·K
e - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
Façade – *ref. Ws11**		**U-0.17 W/m²·K**
a - Custom-size PV panels Megaslate® system	Light grey coloured film	η - 11 % (STC)
b - Air gap	5 cm	
b – Wood particle board / Fermacell®	1.5 cm	λ - 0.14 W/m·K
c – EPS expanded polystyrene (100% recycled)	19 cm	λ - 0.04 W/m·K
b – Wood particle board	1.5 cm	λ - 0.14 W/m·K
e – Ceramic brick	15 cm	λ - 0.47 W/m·K
f – Air gap	6 cm	
g – Ceramic brick	6 cm	λ - 0.47 W/m·K
h - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-0.60 W/m²·K**
a – Ceramic floor tiles	2 cm	λ - 1.30 W/m·K
b – Cement screed	7 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	20 cm	λ - 2.50 W/m·K
d – XPS extruded polystyrene	4 cm	λ - 0.04 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies		
Reinforced concrete slabs	20 cm	-
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-28. Composition of the different parts of the building envelope for scenario S3, Archetype 3. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

Thermal bridge analysis

Table 10-29 shows the possible range of values (min – max) for each type of LTB, considering the constructive details proposed for Archetype 3, using reference values from **[Infomind Sàrl 2003]**. From those ranges, a value is selected for each scenario, as shown in Table 10-30.

Type	Linear thermal bridge description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Flat roof-Wall	1.3-A6	-0.02 -0.04
TB2	Wall-Unheated ground floor	3.4-A1	-0.01 +0.24
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.63 +0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.62+0.84
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-A1	+0.07+0.15
TB9	Jamb at window or door	5.2-A1	+0.08 +0.17
TB10	Lintel above window or door	5.3-A1	+0.07+0.16
TB11	Ventilated façade fixation	6.2-U1	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-29. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]**.

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	+0.04	+0.04	+0.04	+0.04
TB2	+0.09	+0.10	+0.10	+0.07
TB3	+0.14	+0.13	+0.13	+0.11
TB4	+0.71	+0.68	+0.68	+0.63
TB6	+0.68	+0.66	+0.66	+0.62
TB7	-	-	-	+0.25
TB8	+0.10	+0.14	+0.14	+0.15
TB9	+0.15	+0.11	+0.11	+0.12
TB10	+0.11	+0.15	+0.15	+0.16
TB11	-	-	-	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-30. Linear thermal bridges values corresponding to Archetype 3 according to **[Infomind Sàrl 2003]**.

Figure 10-16 shows the insulation strategy (internal or external) and the location of the main thermal bridges. Most of the thermal bridges are easily solvable for this archetype, since external insulation is added in all scenarios. The construction characteristics of Archetype 3 are well represented in the Swiss catalogue so we use standard values according to the existing type of construction and the insulation strategy adopted.

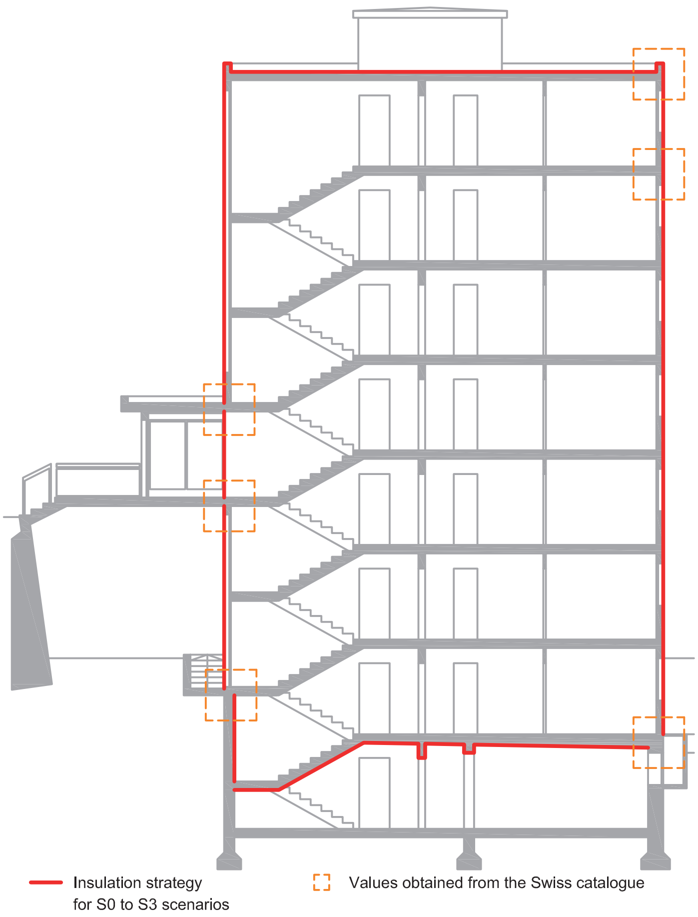


Figure 10-16. Insulation strategy and location of the main thermal bridges for the Archetype 3 (scenarios S0 to S3).

The Glaser diagrams shown in Figure 10-17 and Figure 10-18 confirm the absence of any interstitial condensation risk between the different layers that form the envelope.

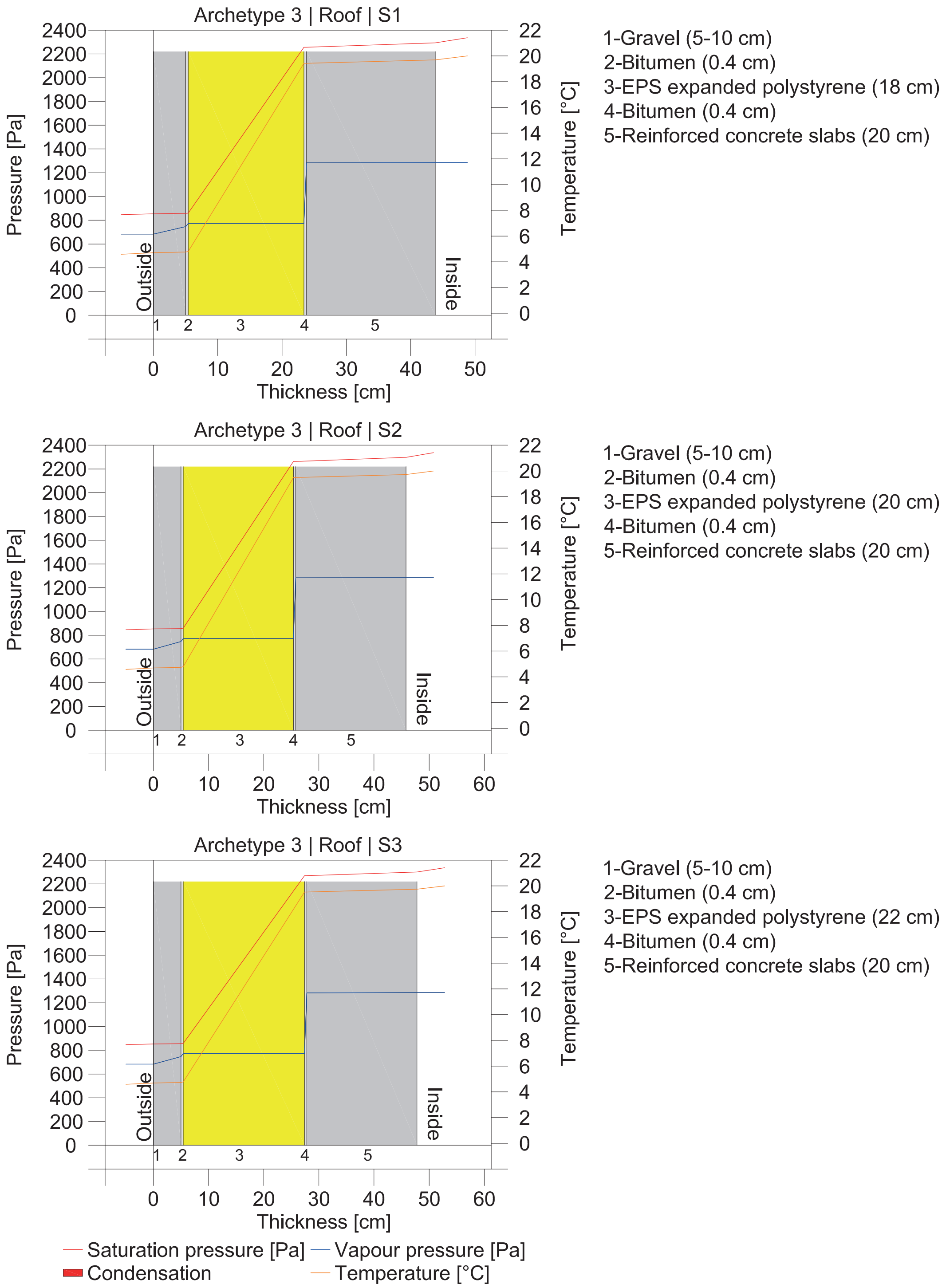


Figure 10-17. Glaser diagram (January, worst case month) corresponding to the flat roof, for scenario S1, S2 and S3, Archetype 3.

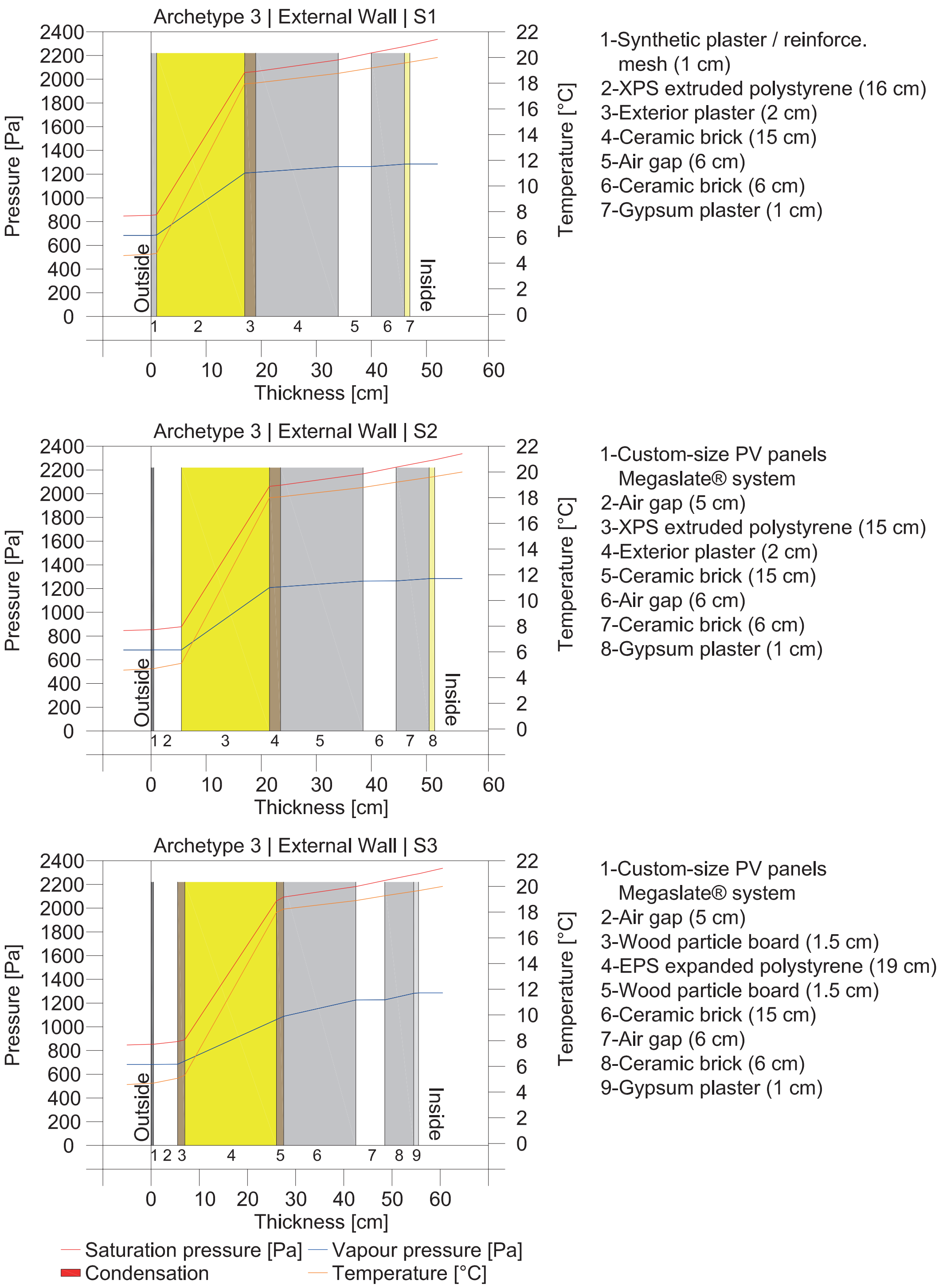


Figure 10-18. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario S1, S2 and S3, Archetype 3.

10.1.6. Archetype 4

Materials description

Table 10-31 to Table 10-35 present the description of the layers composing the building envelope including their thermal / visual characteristics for each scenario for Archetype 4.

E0 – Current status		
Roof – *ref. Ds02**		**U-0.62 W/m²·K**
a – Gravel	5 cm	λ – 0.36 W/m·K
b - Bitumen	0.2 cm	λ – 0.24 W/m·K
c – EPS expanded polystyrene (old)	6 cm	λ - 0.05 W/m·K
d – Cement screed	4 cm	λ – 0.38 W/m·K
e - Bitumen	0.2 cm	λ – 0.24 W/m·K
f - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
g - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Façade – *ref. Ws11**		**U-0.98 W/m²·K**
a - Reinforced concrete	2-14 cm	λ - 2.50 W/m·K
b – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
c - Reinforced concrete	14 cm	λ - 2.50 W/m·K
d - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-2.19 W/m²·K**
a – Linoleum floor	0.5 cm	λ - 0.17 W/m·K
b – Cement screed	5 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
d - Gypsum plaster	1 cm	λ - 0.40 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.44 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	6 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ - 2.50 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies (loggias)		
Reinforced concrete slabs	22 cm	-
Openings **		**U-2.90 W/m²·K**
Wooden frame windows	-	U-1.90 W/m²·K
Double-glazing (with air gap)	6+4+6 mm	U-3.09 W/m²·K
Solar heat gain coefficient - SHGC	0.710	
Visible transmittance coefficient - Tvis	0.781	

Table 10-31. Composition of the different parts of the building envelope for scenario E0, Archetype 4. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S0 – Baseline		
Roof – *ref. Ds02**		**U-0.25 W/m²·K**
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
c – EPS expanded polystyrene	12 cm	λ - 0.04 W/m·K
d – Cement screed	4 cm	λ – 0.38 W/m·K
e - Bitumen	0.2 cm	λ – 0.24 W/m·K
f - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
g - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Façade – *ref. Ws11**		**U-0.25W/m²·K**
a - Reinforced concrete	2-14 cm	λ - 2.50 W/m·K
b – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
c - Reinforced concrete	14 cm	λ - 2.50 W/m·K
d – Mineral wool insulation	10 cm	λ – 0.035 W/m·K
e - Vapour barrier	-	-
f - Plasterboard	1.5 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Linoleum floor	0.5 cm	λ - 0.17 W/m·K
b – Cement screed	5 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) – *ref. Bs14**		**U-2.44 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	6 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ - 2.50 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies (loggias)		
Reinforced concrete slabs	22 cm	-
Openings **		**U-1.30 W/m²·K**
PVC frame windows	-	U-2.20 W/m²·K
Double-glazing (with argon gap)	4-12-4 mm	U-1.25 W/m²·K
Solar heat gain coefficient - SHGC	0.579	
Visible transmittance coefficient - Tvis	0.698	

Table 10-32. Composition of the different parts of the building envelope for scenario S0, Archetype 4. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2016**]; ** Database WINDOW [**LBNL 2017a**] and DesignBuilder [**DesignBuilder 2018**].

S1 – BIPV Conservation		
Roof – *ref. Ds02**		**U-0.20 W/m²·K**
Standard-size PV panels	South	η - 20 % (STC)
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
c – EPS expanded polystyrene	15 cm	λ - 0.04 W/m·K
d – Cement screed	4 cm	λ – 0.38 W/m·K
e - Bitumen	0.2 cm	λ – 0.24 W/m·K
f - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
g - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Façade – *ref. Ws11**		**U-0.20 W/m²·K**
Additional layer with BIPV elements on the window railings:		
a - Custom-size PV panels Megaslate® system	Dark grey coloured film	η - 13 % (STC)
b - Air gap	5 cm	
The rest of the façade:		
a - Reinforced concrete	2-14 cm	λ - 2.50 W/m·K
b – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
c - Reinforced concrete	14 cm	λ - 2.50 W/m·K
d – Mineral wool insulation	14 cm	λ – 0.035 W/m·K
e - Vapour barrier	-	-
f - Plasterboard	1.5 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Linoleum floor	0.5 cm	λ - 0.17 W/m·K
b – Cement screed	5 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.44 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	6 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ - 2.50 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies (loggias)		
Reinforced concrete slabs	22 cm	-
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-33. Composition of the different parts of the building envelope for scenario S1, Archetype 4. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S2 – BIPV Renovation		
Roof – *ref. Ds02**		**U-0.19 W/m²·K**
Standard-size PV panels	South	η - 20 % (STC)
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
c – EPS expanded polystyrene	16 cm	λ - 0.04 W/m·K
d – Cement screed	4 cm	λ – 0.38 W/m·K
e - Bitumen	0.2 cm	λ – 0.24 W/m·K
f - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
g - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Façade – *ref. Ws11**		**U-0.19 W/m²·K**
a - Standard-size PV panels Megaslate® system	Light /dark grey coloured film	η - 11-13 % (STC)
b - Air gap	5 cm	
c – Wood particle board / Fermacell®	1.5 cm	λ - 0.14 W/m·K
d – XPS extruded polystyrene	14 cm	λ - 0.034 W/m·K
e - Reinforced concrete	2-14 cm	λ - 2.50 W/m·K
f– EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
g - Reinforced concrete	14 cm	λ - 2.50 W/m·K
h - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Linoleum floor	0.5 cm	λ - 0.17 W/m·K
b – Cement screed	5 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.44 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	6 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ - 2.50 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies (loggias)		
Reinforced concrete slabs	22 cm	-
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-34. Composition of the different parts of the building envelope for scenario S2, Archetype 4. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S3 – BIPV Transformation

Roof – *ref. Ds02**		**U-0.17 W/m²·K**
Standard-size PV panels	South	η - 20 % (STC)
a – Gravel	5-10 cm	λ – 0.36 W/m·K
b - Bitumen	0.4 cm	λ – 0.24 W/m·K
c – EPS expanded polystyrene	18 cm	λ - 0.04 W/m·K
d – Cement screed	4 cm	λ – 0.38 W/m·K
e - Bitumen	0.2 cm	λ – 0.24 W/m·K
f - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
g - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Façade – *ref. Ws11**		**U-0.17 W/m²·K**
a - Standard-size PV panels Megaslate® system	Light /dark grey coloured film	η - 11-13 % (STC)
b - Air gap	5 cm	
c – Wood particle board / Fermacell®	1.5 cm	λ - 0.14 W/m·K
d – EPS expanded polystyrene (100% recycled)	18 cm	λ - 0.04 W/m·K
e – Wood particle board	1.5 cm	λ - 0.14 W/m·K
f - Reinforced concrete	14 cm	λ - 2.50 W/m·K
g - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Linoleum floor	0.5 cm	λ - 0.17 W/m·K
b – Cement screed	5 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
e - Synthetic plaster	1 cm	λ - 0.18 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.44 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	6 cm	λ - 0.41 W/m·K
c - Reinforced concrete slabs	22 cm	λ - 2.50 W/m·K
Solar protections		
Wooden roller shutter	3 cm	-
Balconies (loggias)		
Reinforced concrete slabs	22 cm	-
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-35. Composition of the different parts of the building envelope for scenario S3, Archetype 4. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

Thermal bridge analysis

Table 10-36 and Table 10-37 show the possible range of values (min – max) for each type of LTB, considering the constructive details proposed for Archetype 4, using reference values from **[Infomind Sàrl 2003]**. From those ranges, a value is selected for each scenario, as shown in Table 10-38.

Type	Linear thermal bridge description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Flat roof-Wall	1.3-I1	+0.47 +0.68
TB2	Wall-Unheated ground floor	3.4-I1	-0.18 +0.05
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.63 +0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.62+0.84
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-I2	+0.09+0.15
TB9	Jamb at window or door	5.2-I4	+0.07 +0.14
TB10	Lintel above window or door	5.3-I1	+0.08+0.13
TB11	Ventilated façade fixation	6.2-U1	ΔU +0.03 $W/m^2·K$

Table 10-36. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]** for scenarios S0 and S1 (façade with internal insulation).

Type	Linear thermal bridge description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Flat roof-Wall	1.3-A6	-0.02 -0.04
TB2	Wall-Unheated ground floor	3.4-A1	-0.01 +0.24
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.63 +0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.62+0.84
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-A1	+0.07+0.15
TB9	Jamb at window or door	5.2-A1	+0.08 +0.17
TB10	Lintel above window or door	5.3-A1	+0.07+0.16
TB11	Ventilated façade fixation	6.2-U1	ΔU +0.03 $W/m^2·K$

Table 10-37. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]** for scenarios S2 and S3 (façade with external insulation).

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	+0.63	+0.61	+0.04	+0.04
TB2	-0.12	-0.08	+0.05	+0.07
TB3	+0.19	+0.17	+0.15	+0.15
TB4	+0.83	+0.78	+0.78	+0.71
TB6	+0.68	+0.66	+0.66	+0.62
TB7	-	-	-	+0.25
TB8	+0.06	+0.10	+0.14	+0.15
TB9	+0.09	+0.13	+0.11	+0.12
TB10	+0.11	+0.11	+0.15	+0.16
TB11	-	-	-	ΔU +0.03 $W/m^2·K$

Table 10-38. Linear thermal bridges values corresponding to Archetype 3 according to **[Infomind Sàrl 2003]**.

Figure 10-19 and Figure 10-20 present the insulation strategy (internal or external) and the location of the main thermal bridges. The construction characteristics of Archetype 4 are well represented in the Swiss catalogue so we use standard values according to the existing type of construction and the insulation strategy adopted.

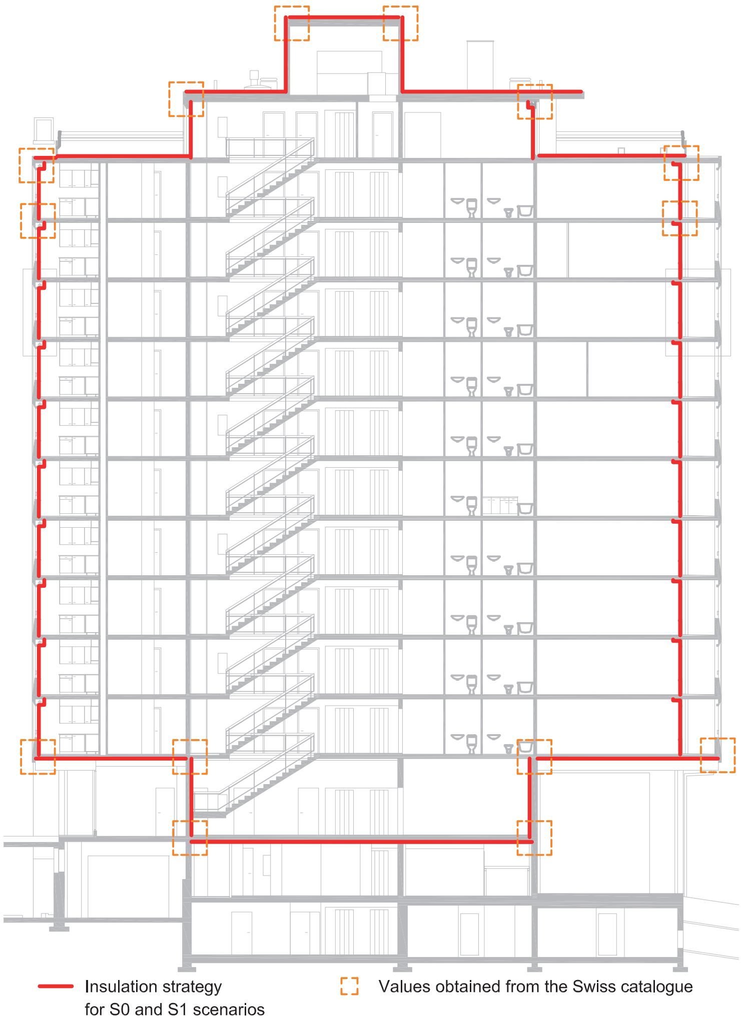


Figure 10-19. Insulation strategy and location of the main thermal bridges for the Archetype 4 (scenarios S0 and S1).

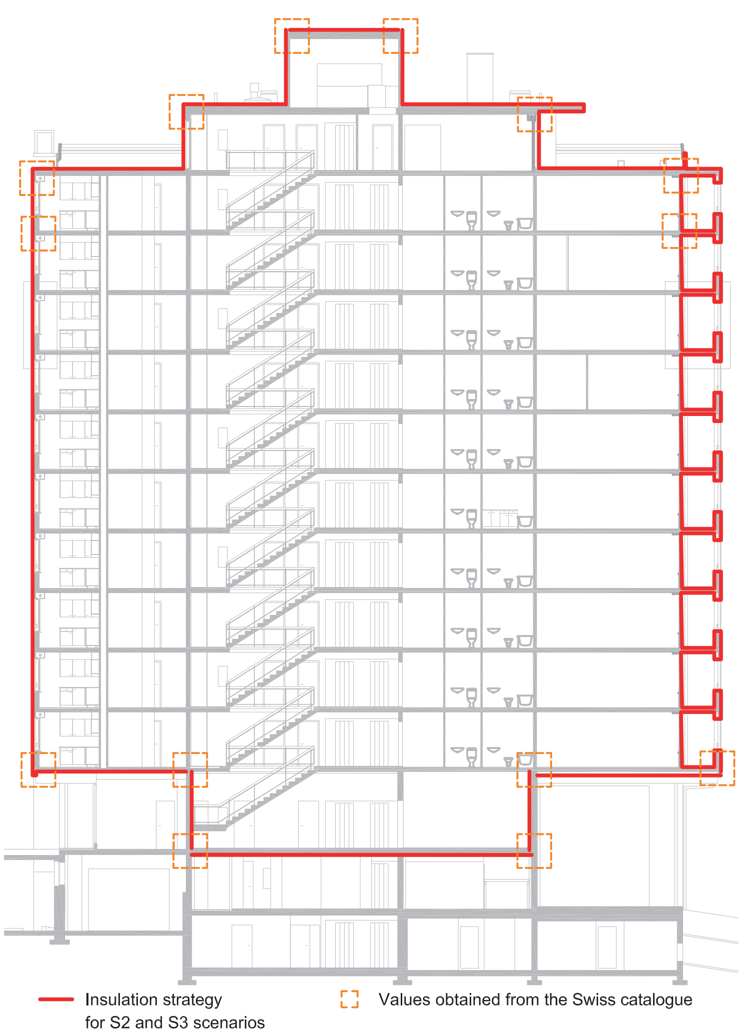


Figure 10-20. Insulation strategy and location of the main thermal bridges for the Archetype 4 (scenarios S2 and S3).

The Glaser diagrams shown in Figure 10-21 to Figure 10-23 confirm the absence of any interstitial condensation risk between the different layers that form the envelope.

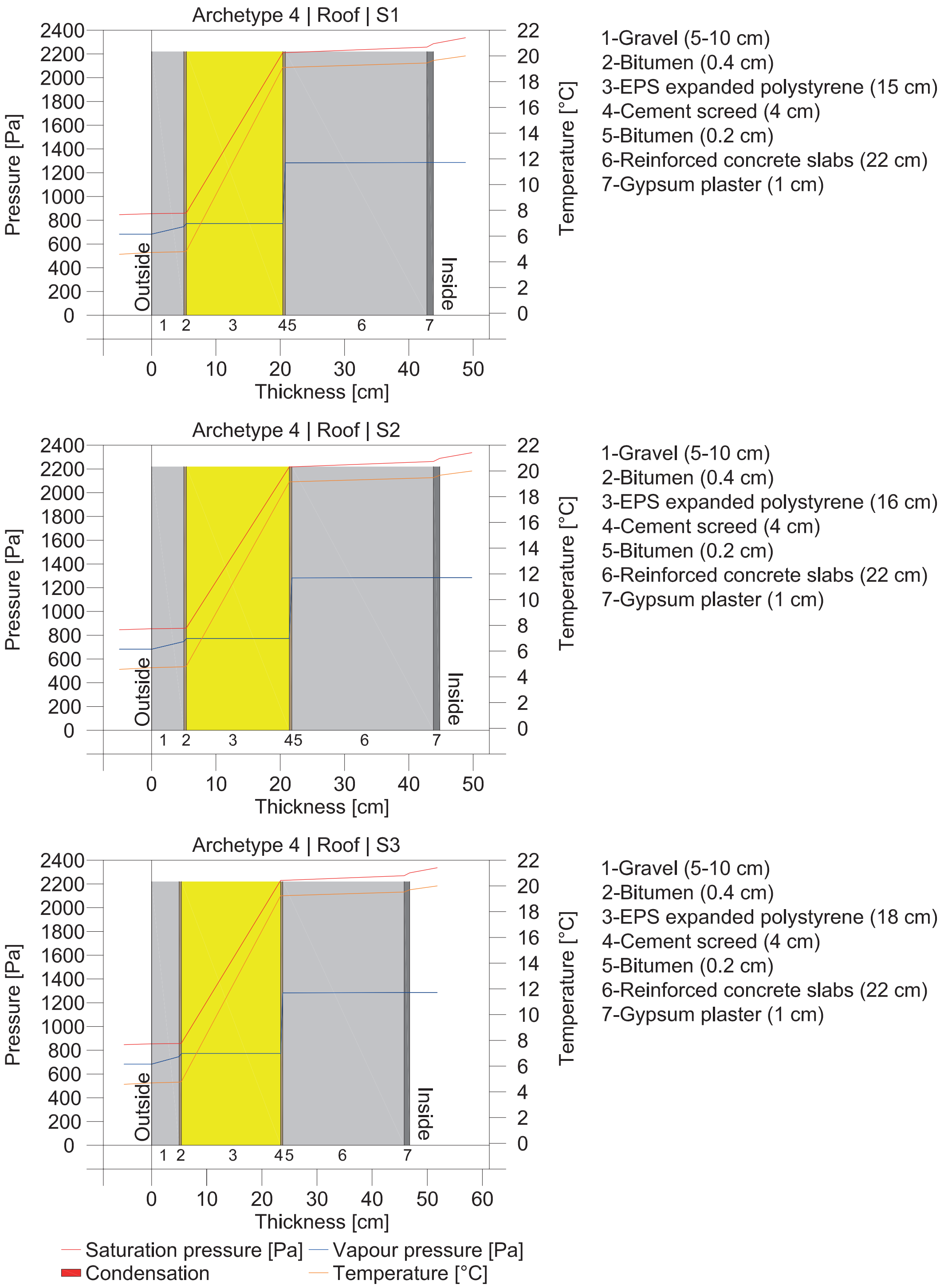


Figure 10-21. Glaser diagram (January, worst case month) corresponding to the flat roof, for scenario S1, S2 and S3, Archetype 4.

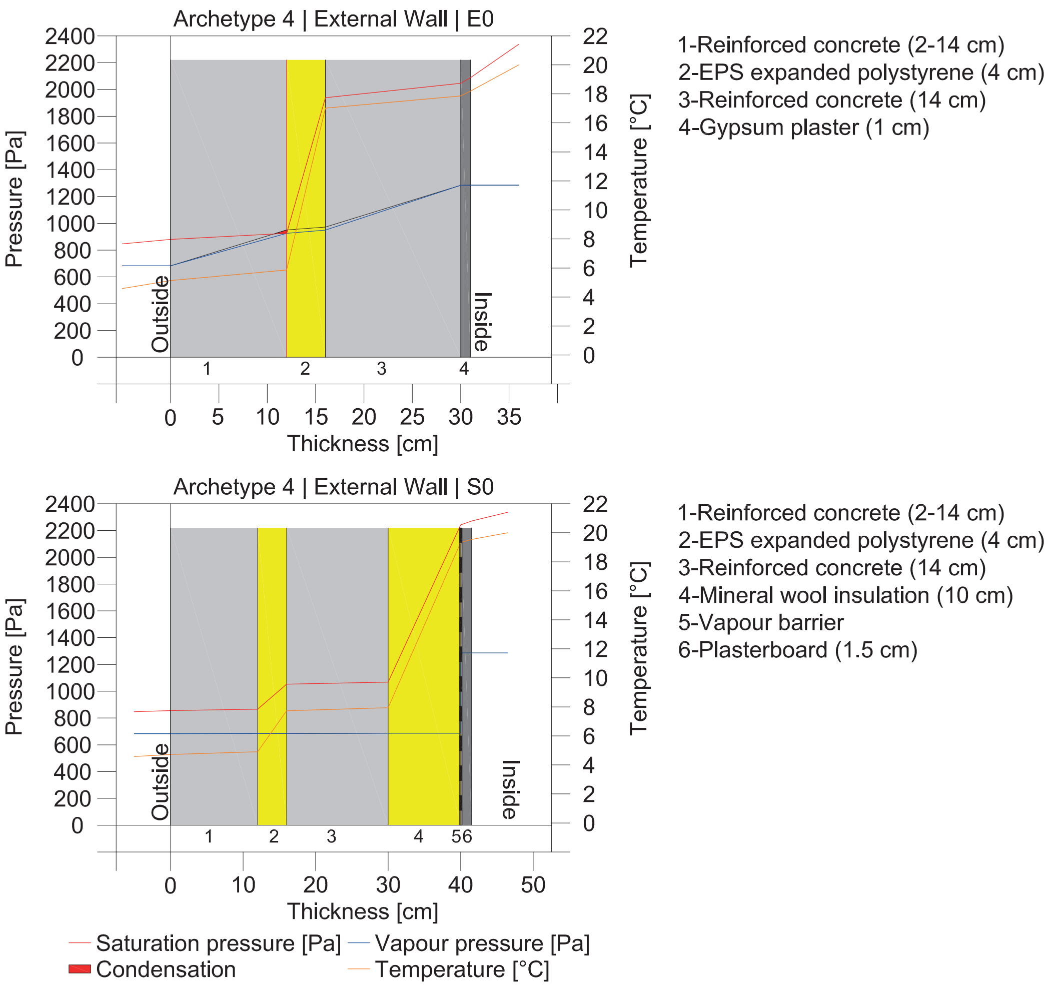


Figure 10-22. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario E0 and S0, Archetype 4.

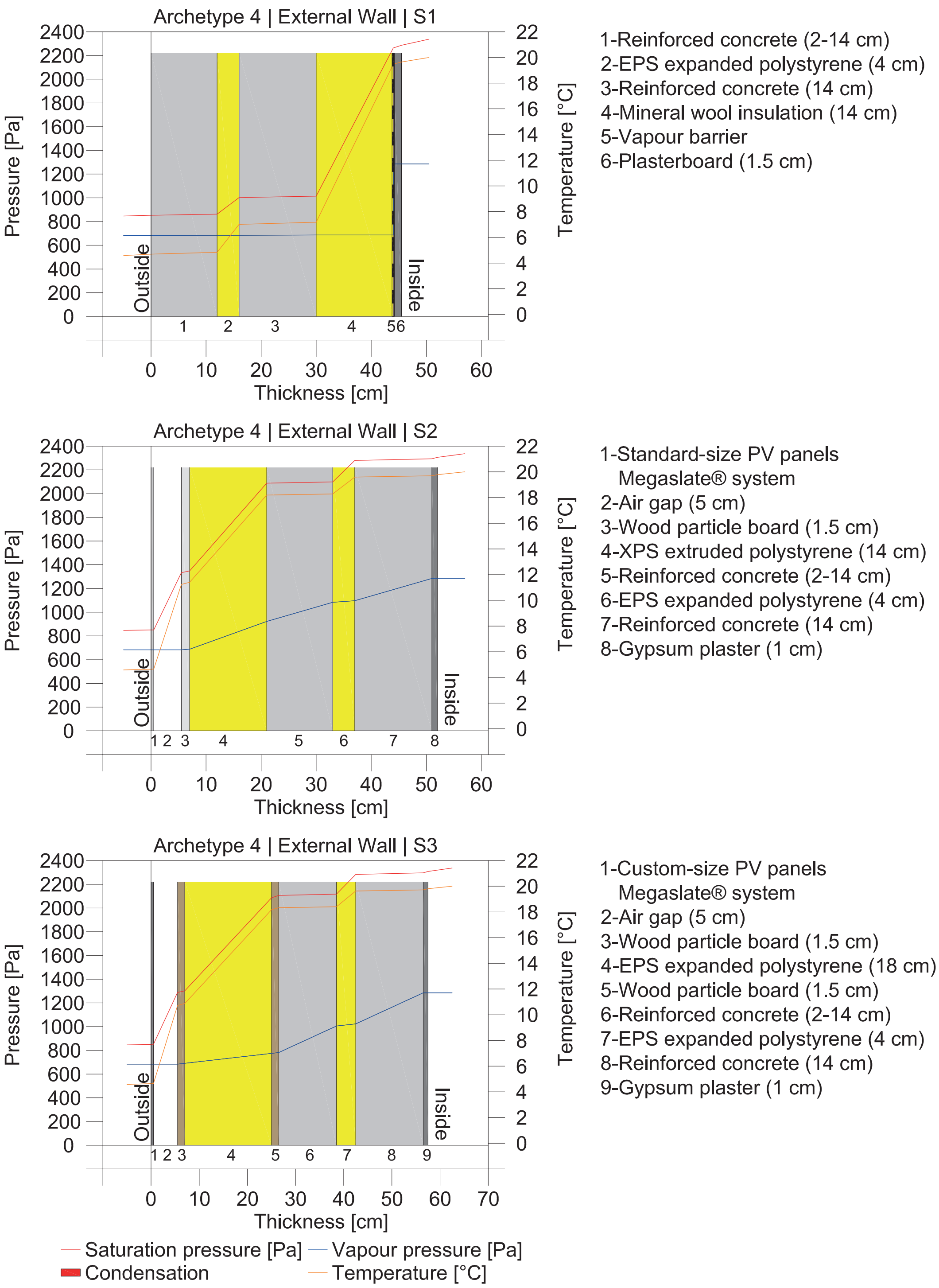


Figure 10-23. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario S1, S2 and S3, Archetype 4.

10.1.7. Archetype 5

Materials description

Table 10-39 to Table 10-43Table 10-35 present the description of the layers composing the building envelope including their thermal / visual characteristics for each scenario for Archetype 5.

E0 – Current status		
Roof curved– *ref. D01**		**U-0.53W/m²·K**
a – Zinc sheet	0.5 cm	λ – 113 W/m·K
b – Air gap	5 cm	-
c – EPS expanded polystyrene (old)	8 cm	λ - 0.05 W/m·K
d – Vapour barrier	-	-
f - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
Roof flat – *ref. Ds02**		**U-0.69W/m²·K**
a – Concrete tiles	2 cm	λ – 1.50 W/m·K
b – XPS extruded polystyrene	4 cm	λ - 0.034 W/m·K
c - Bitumen	0.4 cm	λ – 0.24 W/m·K
d - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
Façade – *ref. Ws11**		**U-0.59 W/m²·K**
a – Ceramic brick	14 cm	λ – 0.47 W/m·K
b – Air gap	4 cm	-
b – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
c - Reinforced concrete	15 cm	λ - 2.50 W/m·K
d - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-1.78 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.01 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
Solar protections		
Exterior aluminium blinds	10 cm	-
Balconies		
Reinforced concrete slabs	30 cm	-
Openings **		**U-2.98 W/m²·K**
Aluminium frame windows	-	U-3.98 W/m²·K
Double-glazing (with air gap)	6+12+6 mm	U-2.70 W/m²·K
Solar heat gain coefficient - SHGC	0.616	
Visible transmittance coefficient - Tvis	0.657	

Table 10-39. Composition of the different parts of the building envelope for scenario E0, Archetype 5. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S0 – Baseline		
Roof curved– *ref. D01**		**U-0.25 W/m²·K**
a – Zinc sheet	0.5 cm	λ – 113 W/m·K
b – Air gap	5 cm	-
c – EPS expanded polystyrene (old)	8 cm	λ - 0.05 W/m·K
d – Vapour barrier	-	-
e - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
f – EPS expanded polystyrene	8 cm	λ - 0.04 W/m·K
g – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Roof flat– *ref. Ds02**		**U-0.25 W/m²·K**
a – Concrete tiles	2 cm	λ – 1.50 W/m·K
b – XPS extruded polystyrene	4 cm	λ - 0.034 W/m·K
c - Bitumen	0.4 cm	λ – 0.24 W/m·K
d - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
e – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Façade – *ref. Ws11**		**U-0.59 W/m²·K**
a – Ceramic brick	14 cm	λ – 0.47 W/m·K
b – Air gap	4 cm	-
b – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
c - Reinforced concrete	15 cm	λ - 2.50 W/m·K
d - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.01 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
Solar protections		
Exterior aluminium blinds	10 cm	-
Balconies		
Reinforced concrete slabs	30 cm	-
Openings **		**U-1.30 W/m²·K**
PVC frame windows	-	U-2.20 W/m²·K
Double-glazing (with argon gap)	4-12-4 mm	U-1.25 W/m²·K
Solar heat gain coefficient - SHGC	0.579	
Visible transmittance coefficient - Tvis	0.698	

Table 10-40. Composition of the different parts of the building envelope for scenario S0, Archetype 5. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2016**]; ** Database WINDOW [**LBNL 2017a**] and DesignBuilder [**DesignBuilder 2018**].

S1 – BIPV Conservation		
Roof curved– *ref. D01**		**U-0.20 W/m²·K**
a -Standard-size PV panels CENIT DESIGN® system [ISSOL 2017]	Black	η - 21.5 % (STC)
c – Zinc sheet	0.5 cm	λ – 384 W/m·K
d – Air gap	5 cm	-
e – EPS expanded polystyrene (old)	8 cm	λ - 0.05 W/m·K
f – Vapour barrier	-	-
g - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
h – EPS expanded polystyrene	12 cm	λ - 0.04 W/m·K
i – Vapour barrier	-	-
j – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Roof flat– *ref. Ds02**		**U-0.25 W/m²·K**
a – Concrete tiles	2 cm	λ – 1.50 W/m·K
b – XPS extruded polystyrene	4 cm	λ - 0.034 W/m·K
c - Bitumen	0.4 cm	λ – 0.24 W/m·K
d - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
e – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Façade – *ref. Ws11**		**U-0.20 W/m²·K**
a – Ceramic brick	14 cm	λ – 0.47 W/m·K
b – Air gap	4 cm	-
b – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
c - Reinforced concrete	15 cm	λ - 2.50 W/m·K
d – EPS expanded polystyrene	13 cm	λ - 0.04 W/m·K
e – Vapour barrier	-	-
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.01 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
Solar protections		
Exterior aluminium blinds	10 cm	-
Balconies		
Reinforced concrete slabs	30 cm	-
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-41. Composition of the different parts of the building envelope for scenario S1, Archetype 5. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S2 – BIPV Renovation		
Roof curved– *ref. D01**		**U-0.19 W/m²·K**
a -Standard-size PV panels CENIT DESIGN® system [ISSOL 2017]	Black	η - 21.5 % (STC)
c – Zinc sheet	0.5 cm	λ – 384 W/m·K
d – Air gap	5 cm	-
e – EPS expanded polystyrene (old)	8 cm	λ - 0.05 W/m·K
f – Vapour barrier	-	-
g - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
h – EPS expanded polystyrene	13 cm	λ - 0.04 W/m·K
i – Vapour barrier	-	-
j – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Roof flat– *ref. Ds02**		**U-0.25 W/m²·K**
a – Concrete tiles	2 cm	λ – 1.50 W/m·K
b – XPS extruded polystyrene	4 cm	λ - 0.034 W/m·K
c - Bitumen	0.4 cm	λ – 0.24 W/m·K
d - Reinforced concrete slab	22 cm	λ – 2.50 W/m·K
e – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Façade – *ref. Ws11**		**U-0.19 W/m²·K**
a - Custom-size PV panels brick like	Yellow coloured film	η - 11 % (STC)
b - Air gap	5 cm	
c – XPS extruded polystyrene	12 cm	λ - 0.034 W/m·K
d – Ceramic brick	14 cm	λ – 0.47 W/m·K
e – Air gap	4 cm	-
f – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
g - Reinforced concrete	15 cm	λ - 2.50 W/m·K
h - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.01 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
Solar protections		
Exterior aluminium blinds	10 cm	-
Balconies		
Reinforced concrete slabs	30 cm	-
Custom-size PV panels on railing	Light grey coloured film	η - 11 % (STC)
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-42. Composition of the different parts of the building envelope for scenario S2, Archetype 5. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue [**Suisse Energie 2009, 2016**]; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

S3 – BIPV Transformation		
Roof curved– *ref. D01**		**U-0.17 W/m²·K**
a -Standard-size PV panels CENIT DESIGN® system [ISSOL 2017]	Black	η - 21.5 % (STC)
d – Air gap	5 cm	-
h – EPS expanded polystyrene	22 cm	λ - 0.04 W/m·K
e – Vapour barrier	-	-
f - Reinforced concrete slabs	20 cm	λ – 2.50 W/m·K
Roof flat– *ref. Ds02**		**U-0.25 W/m²·K**
a – Concrete tiles	2 cm	λ – 1.50 W/m·K
b – XPS extruded polystyrene	4 cm	λ - 0.034 W/m·K
c - Bitumen	0.4 cm	λ – 0.24 W/m·K
d - Reinforced concrete slabs	22 cm	λ – 2.50 W/m·K
e – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
Façade – *ref. Ws11**		**U-0.17 W/m²·K**
a - Custom-size PV panels Megaslate® system	Light grey coloured film	η - 11 % (STC)
b - Air gap	5 cm	
c – Wood particle board / Fermacell®	1.5 cm	λ - 0.14 W/m·K
d – EPS expanded polystyrene (100% recycled)	15 cm	λ - 0.04 W/m·K
e – Wood particle board	1.5 cm	λ - 0.14 W/m·K
d – Ceramic brick	14 cm	λ – 0.47 W/m·K
e – Air gap	4 cm	-
f – EPS expanded polystyrene (old)	4 cm	λ - 0.05 W/m·K
g - Reinforced concrete	15 cm	λ - 2.50 W/m·K
h - Gypsum plaster	1 cm	λ - 0.40 W/m·K
Internal floor (against non-heated space) – *ref. Bs03a**		**U-0.32 W/m²·K**
a – Timber floor	1 cm	λ - 0.14 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
d – EPS expanded polystyrene	10 cm	λ - 0.04 W/m·K
f – Plasterboard	1.5 cm	λ - 0.16 W/m·K
External floor (ground) **–** *ref. Bs14**		**U-2.01 W/m²·K**
a – Ceramic floor tiles	1 cm	λ - 1.30 W/m·K
b – Cement screed	4 cm	λ – 0.41 W/m·K
c - Reinforced concrete slabs	30 cm	λ – 2.50 W/m·K
Solar protections		
Exterior aluminium blinds	10 cm	-
Balconies		
Reinforced concrete slabs	30 cm	-
Custom-size PV panels on railing	Light grey coloured film	η - 11 % (STC)
Openings **		**U-0.77 W/m²·K**
Wooden frame windows	-	U-1.80 W/m²·K
Triple-glazing (with argon gap)	4-12-6-12-4 mm	U-0.68 W/m²·K
Solar heat gain coefficient - SHGC	0.443	
Visible transmittance coefficient - Tvis	0.633	

Table 10-43. Composition of the different parts of the building envelope for scenario S3, Archetype 5. Layers and values in red are implemented / modified in this renovation scenario. Layers and materials according to data from: * Swiss construction catalogue **[Suisse Energie 2009, 2016]**; ** Database WINDOW **[LBNL 2017a]** and DesignBuilder **[DesignBuilder 2018]**.

Thermal bridge analysis

Table 10-44 and Table 10-45Table 10-19 show the possible range of values (min – max) for each type of LTB, considering the constructive details proposed for Archetype 5, using reference values from **[Infomind Sàrl 2003]**. From those ranges, a value is selected for each scenario, as shown in Table 10-46Table 10-20.

Type	Linear thermal bridge description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Flat roof-Wall	1.3-I1	+0.47 +0.68
TB2	Wall-Unheated ground floor	3.4-I1	-0.18 +0.05
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.63 +0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.62+0.84
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-I2	+0.09+0.15
TB9	Jamb at window or door	5.2-I4	+0.07 +0.14
TB10	Lintel above window or door	5.3-I1	+0.08+0.13
TB11	Ventilated façade fixation	6.2-U1	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-44. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]** for scenarios S0 and S1 (façade with internal insulation).

Type	Linear thermal bridge description	Ref. in Catalogue	Value range Ψ [W/m-K]
TB1	Flat roof-Wall	1.3-A6	-0.02 -0.04
TB2	Wall-Unheated ground floor	3.4-A1	-0.01 +0.24
TB3	Wall (Ext) –Wall (Int)	2.3-I1	+0.11 +0.24
TB4	Wall-Floor (Int – not ground floor)	2.1-I1	+0.63 +0.89
TB6	Wall-Floor (Ext – balcony)	1.1-Z1	+0.62+0.84
TB7	Blind box	4.2-A1	+0.18 +0.26
TB8	Still below window	5.1-A1	+0.07+0.15
TB9	Jamb at window or door	5.2-A1	+0.08 +0.17
TB10	Lintel above window or door	5.3-A1	+0.07+0.16
TB11	Ventilated façade fixation	6.2-U1	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-45. Value range of linear thermal bridges according to **[Infomind Sàrl 2003]** for scenarios S2 and S3 (façade with external insulation).

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	+0.63	+0.61	+0.04	+0.04
TB2	-0.12	-0.08	+0.05	+0.07
TB3	+0.19	+0.17	+0.15	+0.15
TB4	+0.83	+0.78	+0.78	+0.71
TB6	+0.68	+0.66	+0.66	+0.62
TB7	-	-	-	+0.25
TB8	+0.06	+0.10	+0.14	+0.15
TB9	+0.09	+0.13	+0.11	+0.12
TB10	+0.11	+0.11	+0.15	+0.16
TB11	-	-	-	ΔU +0.03 $W/m^2{\cdot}K$

Table 10-46. Linear thermal bridges values corresponding to Archetype 5 according to **[Infomind Sàrl 2003]**.

Figure 10-24 and Figure 10-25Figure 10-20 present the insulation strategy (internal or external) and the location of the main thermal bridges. The construction characteristics of Archetype 5 are well represented in the Swiss catalogue so we use standard values according to the existing type of construction and the insulation strategy adopted.

Still, a detailed thermal bridges analysis is made at the window lintel (TB10). Results in Figure 10-26 (LTB) and Figure 10-27 (condensation and mould risk) show that a reduction of the 83% in the thermal losses could be achieved comparing S3 to E0. Table 10-47 presents a comparison between the values obtained directly from the Swiss catalogue and those obtained from the detailed study.

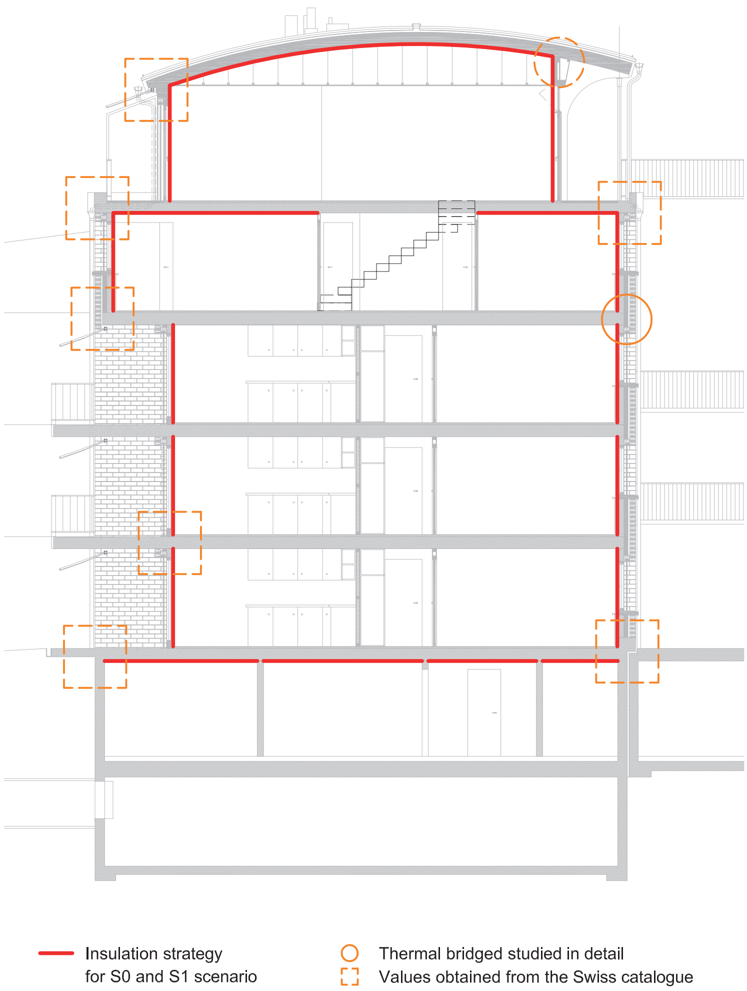


Figure 10-24. Insulation strategy and location of the main thermal bridges for the Archetype 5 (scenarios S0 and S1).

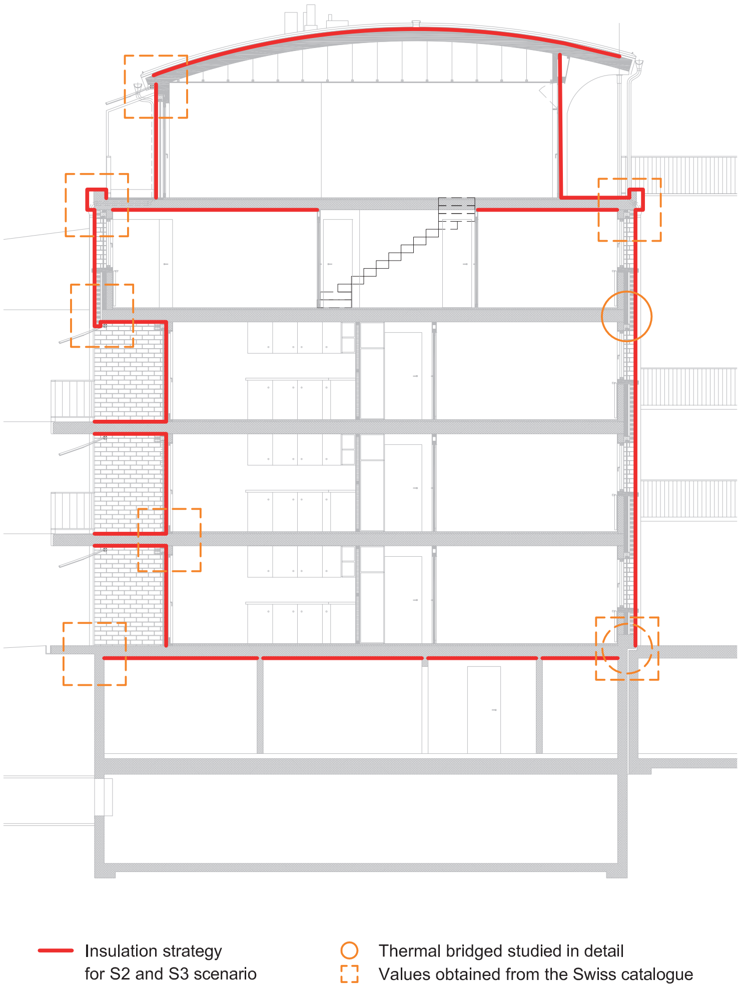


Figure 10-25. Insulation strategy and location of the main thermal bridges for the Archetype 5 (scenarios S2 and S3).

TB10 – Archetype 5	Ψ [W/m·K] for each renovation scenario	
	S2	S3
Values from catalogue	+0.15	+0.16
Values from THERM study	**+1.052**	**+0.163**

Table 10-47. Comparison between the thermal bridges values from the Swiss catalogue and the detailed study.

It is important to highlight that by maintaining the existing blind box, the effect of the external insulation is reduced because of the important thermal bridge generated. This point needs to be improved to bring the LTB value closer to the reference value of the Swiss catalogue (S2). However, in the case of scenario S3, the value obtained is in accordance with the reference value.

From the condensation and mould risk analysis (Figure 10-27), we observe that the E0 and S2 show risks of mould formation near the window frame. For S2, this indicates once again the necessity to improve the insulation of the blind box.

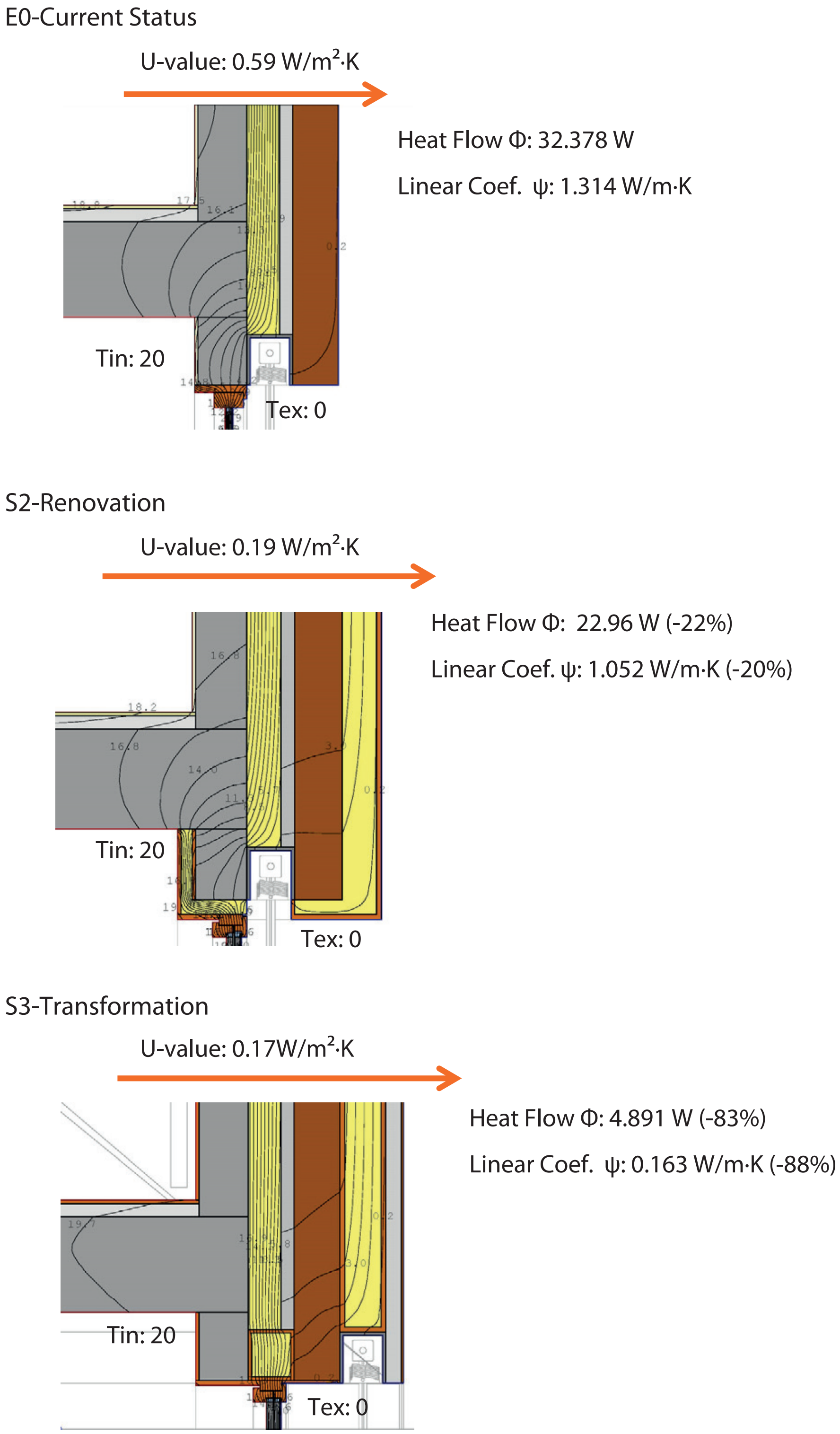
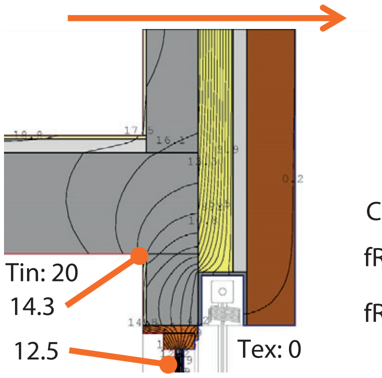


Figure 10-26. Window lintel thermal bridges analysis (TB10) for scenarios E0, S2, and S3, for Archetype 5.

E0-Current Status

U-value: 0.59 W/m²·K



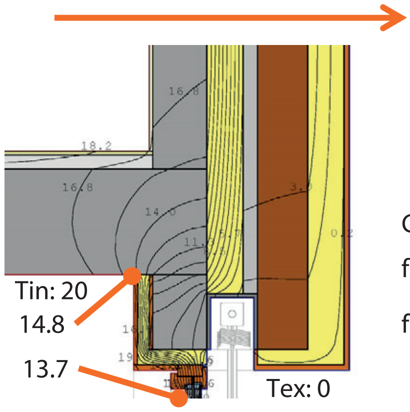
Condensation and mould risk (SIA 180)

fRsi (Cond.) = 0.704 > 0.59

fRsi (Moisi.) = 0.713 < 0.75 (!)

S2-Renovation

U-value: 0.19 W/m²·K



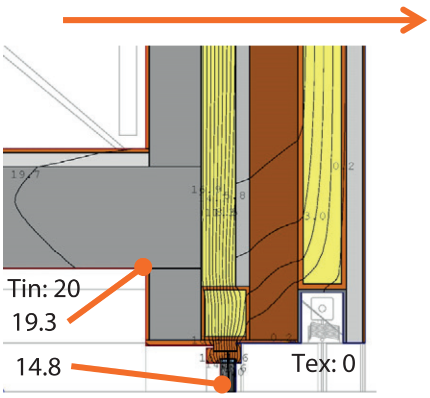
Condensation and mould risk (SIA 180)

fRsi (Cond.) = 0.720 > 0.59

fRsi (Moisi.) = 0.713 < 0.75 (!)

S3-Transformation

U-value: 0.17W/m²·K



Condensation and mould risk (SIA 180)

fRsi (Cond.) = 0.968 > 0.59

fRsi (Moisi.) = 0.963 > 0.75

Figure 10-27. Window lintel thermal bridges analysis (TB10) for scenarios E0, S2, and S3, for Archetype 5.

Type	Ψ [W/m·K] for each renovation scenario			
	S0	S1	S2	S3
TB1	+0.63	+0.61	+0.04	+0.04
TB2	-0.12	-0.08	+0.05	+0.07
TB3	+0.19	+0.17	+0.15	+0.15
TB4	+0.83	+0.78	+0.78	+0.71
TB6	+0.68	+0.66	+0.66	+0.62
TB7	-	-	-	+0.25
TB8	+0.06	+0.10	+0.14	+0.15
TB9	+0.09	+0.13	+0.11	+0.12
TB10	+0.11	+0.11	**+1.05**	**+0.16**
TB11	-	-	-	ΔU +0.03 W/m²·K

Table 10-48. Linear thermal bridges values used for the Archetype 5.

The Glaser diagrams shown in Figure 10-28 and Figure 10-29 confirm the absence of any interstitial condensation risk between the different layers that form the envelope.

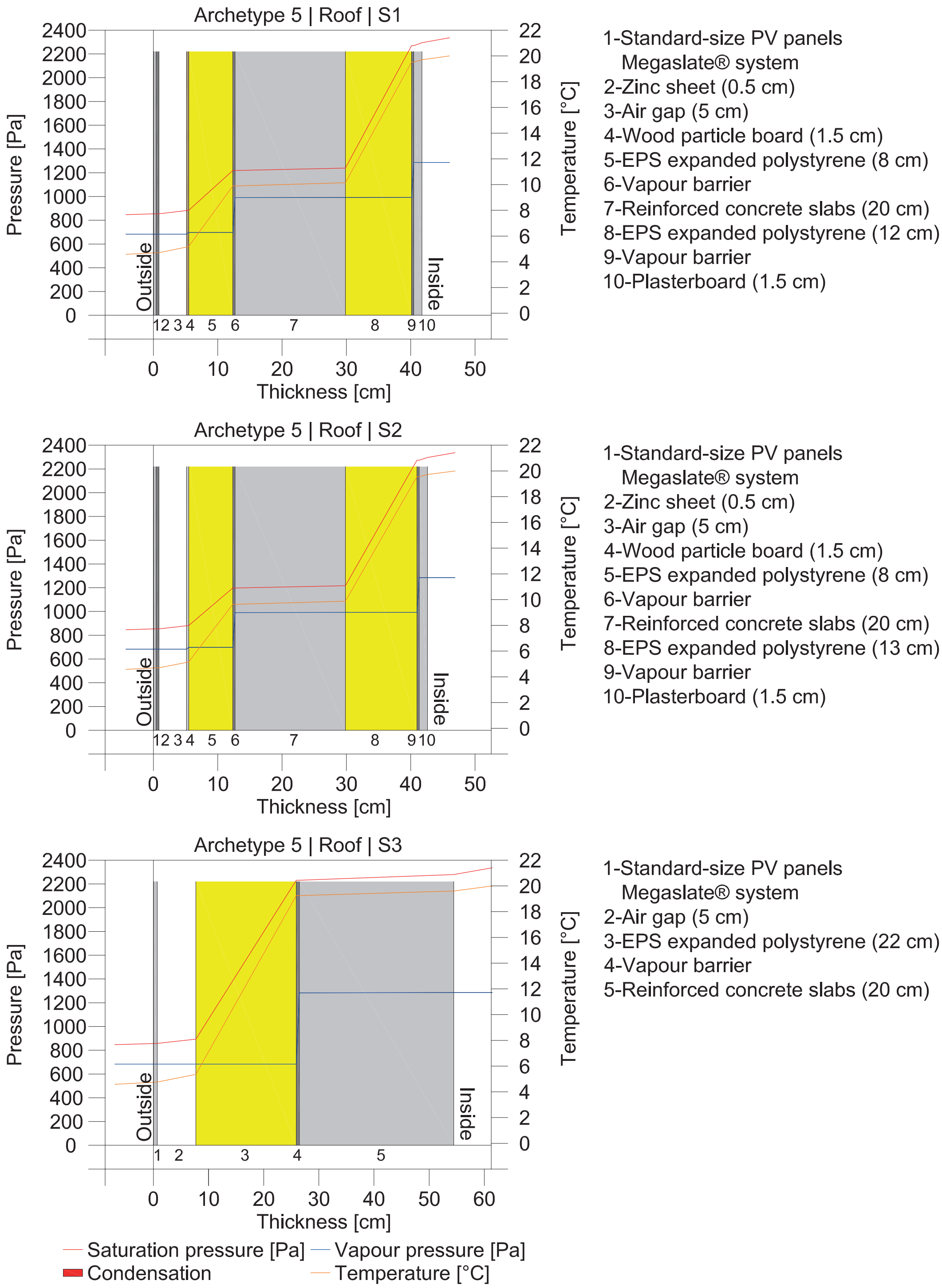


Figure 10-28. Glaser diagram (January, worst case month) corresponding to the flat roof, for scenario S1, S2 and S3, Archetype 5.

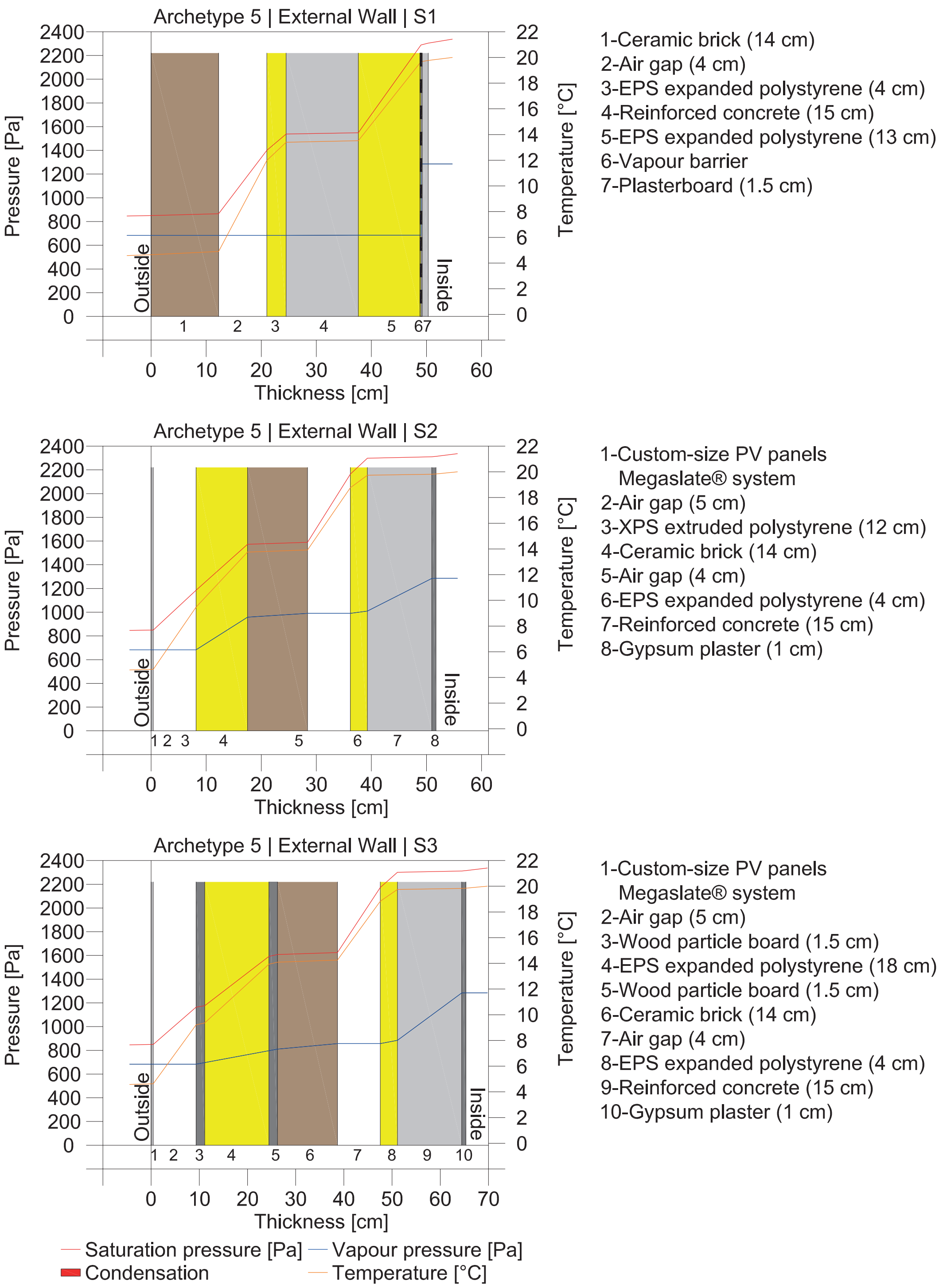


Figure 10-29. Glaser diagram (January, worst case month) corresponding to the external wall, for scenario S1, S2 and S3, Archetype 5.

10.2. Energy model and simulation assumptions

This section presents complementary information to what is provided in Chapters 5, 6 and 7, related to the creation of the energy models and the simulation assumptions.

Activity and use of the building

The energy model is configured using normalised data published in SIA 2024 **[SIA 2015a]** for multi-family buildings, shown in Table 10-49.

Activity – Multi-Family buildings		Value	Units
Occupation rate	*Depending on the specific case study*	0.0342 – 0.0380	person/m^2
		26 - 29	m^2/person
Metabolic rate	Factor (Men=1, Women=0.85, Children=0.75)	0.90	-
	Metabolic activity	1.2	met
	Internal load (at < 24ºC)	70	W/person
	Humidity production (at < 24ºC)	80	g/h
Clothing rate	Winter Clothing	1	clo
	Summer Clothing	0.5	clo
Domestic Hot Water	Consumption	0.876	litres/m^2·day
Heating	Set point Temperatures		
	Set point	20	°C
	Set back	17	°C
Cooling	Set point Temperatures		
	Set point	25	°C
	Set back	27	°C
Humidity Control	*Without humidity control*		
Ventilation	**Natural ventilation**		
	Indoor min temperature control	*By user opening windows*	
	Min Temperature	22	°C
	Minimum Fresh Air	10	litres/s·person
	Mechanical ventilation		
	Minimum Fresh Air	10	litres/s·person
Lighting	Target illuminance	150	Lux
	Default display lighting density	2.7	W/m^2
Electric equipment	Density	4	W/m^2

Table 10-49. Input parameters in reference to the activity and use of the building according to **[SIA 2015a]**.

Schedule (user profiles)

Figure 10-30 and Figure 10-31 present the normalised daily schedules proposed by the SIA 2024 [**SIA 2015a**].

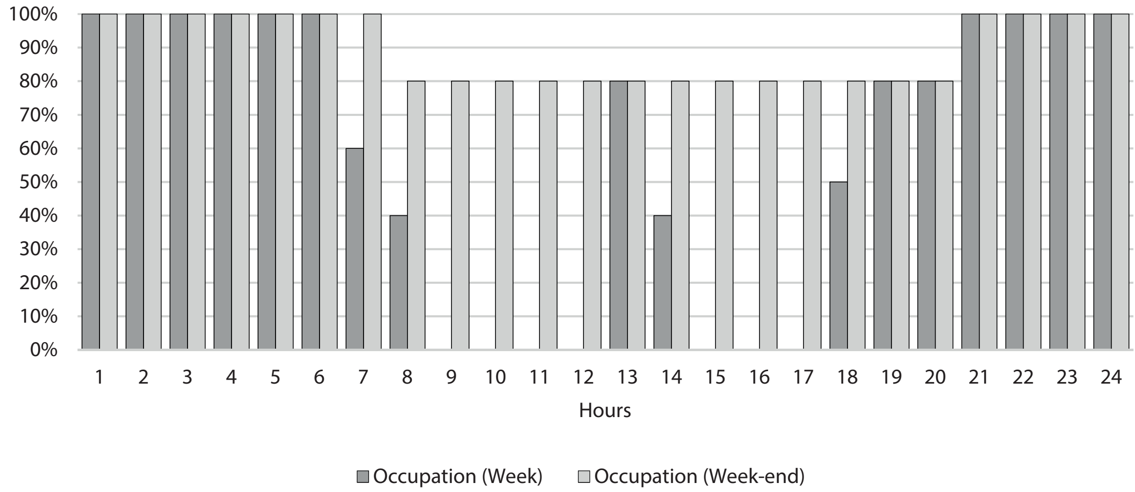


Figure 10-30. Daily occupancy factor according to [**SIA 2015a**].

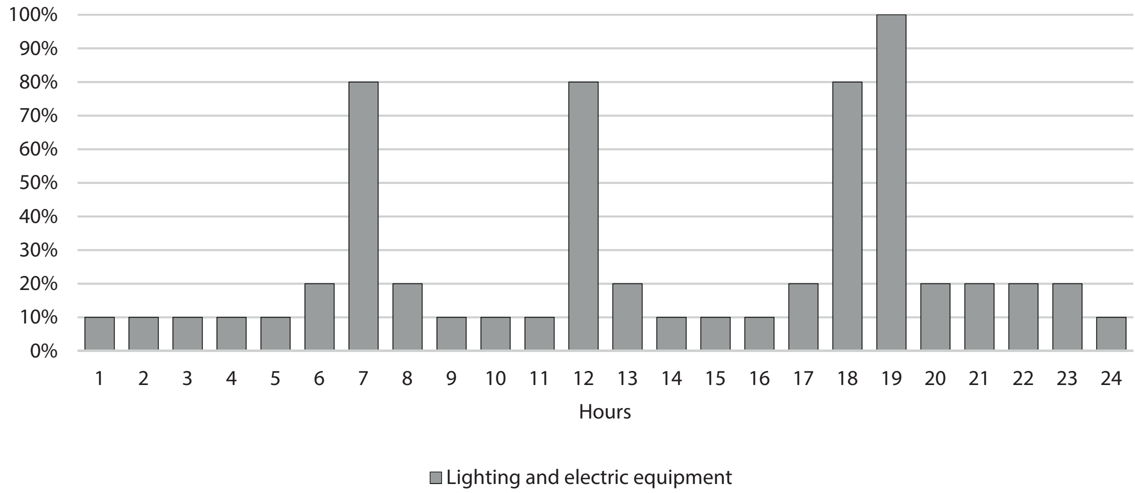


Figure 10-31. Daily use factor for lighting and electric equipment according to [**SIA 2015a**].

HVAC system performance

The Coefficient of Performance (COP) of the different HVAC systems are taken, as suggested in SIA 380/1:2016 [**SIA 2016e**].

	Oil-boiler	Gas-boiler	Air-water Heat-Pump
COP - Heating	0.85	0.93	3.00
COP - DWW	0.66	0.73	2.73

Table 10-50. Coefficient of Performance of different HVAC systems suggested by [**SIA 2016e**].

Current legal requirement (SIA 380/1:2016)

In order to check if our renovation scenarios comply with the minimum legal requirements, the SIA 380/1:2016 **[SIA 2016a]** is used. This norm proposes two methods to justify the project, the first option (the most simplified) consists in using minimum U-values and the second one (used in this thesis) consists in calculating a global energy performance, for which a limit in the heating energy demand (Qhli,re) for existing buildings is set, depending on the type of building:

Qhli,re = 1.5·[Qhli0 + **ΔQhli (Ath/AE)**]**·fcor**

Where

Qhli,re: Heating needs limit **[kWh/m²·year]**

Qhli0: Base heating needs limit **[kWh/m²·year]** (13 kWh/m²·year for multi-family buildings)

ΔQhli: Margin of heating needs limit **[kWh/m²·year]** (15 kWh/m²·year for multi-family buildings)

Ath: Building envelope area **[m²]**

AE: Energy reference floor area **[m²]**

fcor: Temperature correction factor **[-]**

With

fcor = 1 + [(9.4°C-Φe,avg)·0.06K-1

Where

fcor: Temperature correction factor **[-]**

Φe,avg: Outside average temperature **[°C]**

10.3. Economic verification of BIPV sizing method

This section presents an example of the results from a simplified economic study to verify the consistency with our BIPV sizing approach (presented in Chapter 7, Section 7.2.4) and the influence of the different economic parameters (e.g. subsidies and feed-in-tariff). Results presented correspond to Archetype 1, S3-Tranformation.

The analysis consists in calculating the difference between the incomes generated by the BIPV installation (during an estimated lifetime of 25 years) and the investment cost. This indicator allows us to identify the recommended irradiation threshold in order to achieve the maximum profitability or simply the break-even point (*"seuil de rentabilité"*) when the difference between incomes and investment cost becomes greater than or equal to zero. The break-even point depends on different parameters: 1) BIPV cost, 2) purchase energy price for electricity, 3) public subsidies and 4) Feed-in-tariff received in exchange for the overproduction injected into the grid.

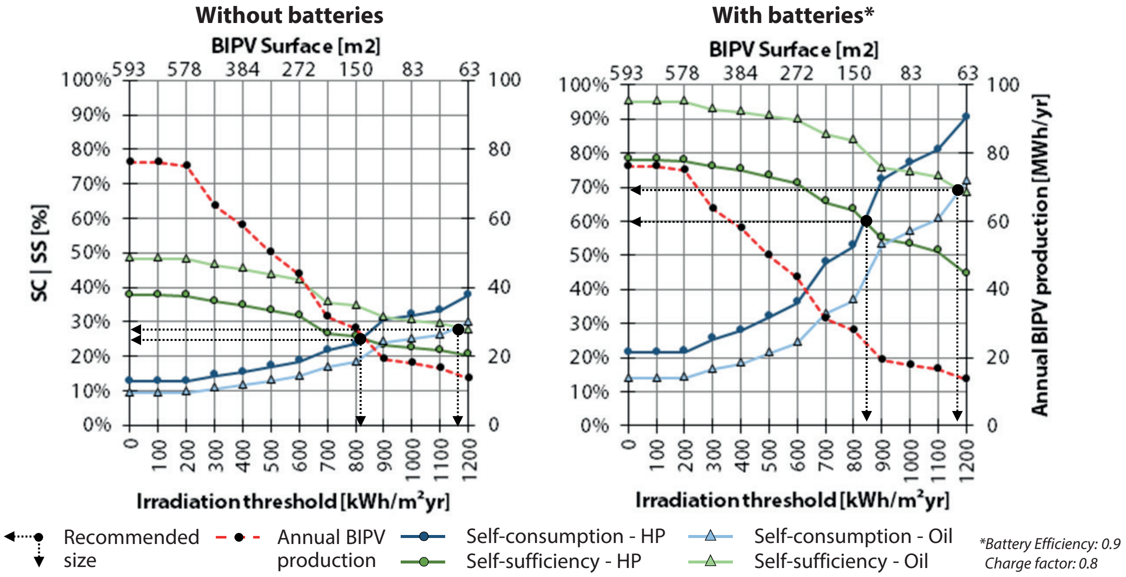


Figure 10-32. Active surfaces selection method applied for Archetype 1, S3-Transformation, with and without batteries.

Incomes (I): corresponds to the amount saved with the self-consumed energy, avoiding purchasing this energy from the grid (over the25-year lifetime), including the amount received for the energy injected into the grid (Feed-in-tariff).

$$I = \frac{(SC \cdot ELcost + OP \cdot FiT) \cdot n}{ERA}$$

Where:

I:	Incomes **[CHF/m²]**
SC:	Self-consumed energy (per year) **[kWhe-pv/year]**
ELcost:	Electricity cost **[CHF/kWhe-grid]** – (0.25 CHF/kWhe-grid)
OP:	Overproduction of energy, injected into the grid (per year) **[kWhe-pv/year]**
FiT:	Feed-in-Tariff **[CHF/kWhe-pv]** – (0.037 – 0.1942 CHF/kWhe-pv)
n:	Expected lifetime **[years]** – (25 years)
ERA:	Energy Reference Area **[m²]**

Cost (C): corresponds to the investment cost taking into account subsides or public aids.

$$C = \frac{C_{BIPV} - (S_{PRU/GRU} + S_{TR} + S_{NB})}{ERA}$$

Where:

C:	Cost **[CHF/m²]**
CBIPV:	BIPV installation cost (incl. batteries) [**CHF**]
SPRU/GRU:	Federal subsidies (P/GRU: small/large unique sum) for BIPV installations [**CHF**] – (~ 30% of CBIPV)
STR:	Amount corresponding to the tax reduction [**CHF**] – (~ 11 - 17% of CBIPV)
SNB:	Communal subsidies for PV installations (Neuchâtel bonus) [**CHF**] – (500 CHF/kWp; Max. 10'000 CHF)
ERA:	Energy Reference Area [**m²**]

Figure 10-33 shows the results for four different scenarios in terms of presence / absence of Feed-in-Tariff (FiT) and Subsidies (SPRU/GRU; STR; SNB), and for a case with and without batteries, leading to a total of eight graphs. Each graph shows the results for the case with the oil/gas boiler and the case with the heat-pump system. For scenarios with a FiT, the current values are considered, i.e. 0.1096 CHF/kWhe-pv.

The first row of graphs shows the case where no FiT and no Subsidies are considered (with / without batteries). In this case – taking into account current prices of the BIPV products – the intervention becomes cost-effective only with storage possibilities and at a high irradiation threshold (>1'000 kWh/m^2·year), corresponding to the most exposed surfaces on the roof.

When Subsidies are considered (second row of graphs), these help with the initial investment and encourage to use the most exposed part of the façade. The irradiation threshold values are then consistent with the ones obtained through the active surfaces selection method (Figure 10-32), which are between 900 to 1'200 kWh/m^2·year if no batteries are installed and between 600 to 1'200 kWh/m^2·year if batteries are considered.

The third row of graphs shows the case where only a FiT is considered. Results demonstrate that a FiT encourages to install the largest installation possible, almost independently of the irradiation threshold as BIPV on surfaces with low-levels of annual irradiation (200-400 kWh/m^2·year) become cost-effective. This trend is contrary to the reasonable design of the installation in line with the needs of the building using the SC and SS indicators. Thus, the FiT parameter does not help to filter correctly the active surfaces to obtain an installation well adapted to the needs of the building since it encourages the injection in the grid.

The fourth row of graphs correspond to the case where both FiT and Subsidies are considered and the results show the same trend as if only FiT was considered (the FiT dominates with respect to the Subsidies).

It important to highlight that in all scenarios the break-even point depends on the intervention on the HVAC system. In general, if the oil/gas-boiler is maintained, the range of recommended irradiation threshold is narrower and begins at higher values compared to using an electric heat-pump for heating and DHW.

As expected, results show that an installation using all possible active surfaces (without any filtering condition, corresponding to an irradiation threshold of 0 kWh/m^2·year) is not recommended in any case, because the priority should be the maximisation of the amount of energy self-consumed by the building itself, avoiding as much as possible the injection into the grid in exchange of progressively decreasing FiT.

Currently, taking into account the investment subsidies [**OFEN 2018d; Ville de Neuchâtel 2018**], it is necessary to compensate the still high prices of BIPV products during a transition period (waiting for the demand for this type of products to augment naturally and the prices to readjust). However, regarding the FiT, it is recommended to consider it for the global economic calculation – assuming a decrease of 5%/year following the trend of the last four years **[VESE 2018]** – but not for sizing the BIPV installation. This conclusion is consistent with the approach of the emerging policies that aim to encourage the integration of photovoltaic energy in the existing building stock **[EnDK 2014; Suisse Energie et al. 2015; AFCF 2018; OFEN 2018d, 2018e, 2018f; SIG 2018]**.

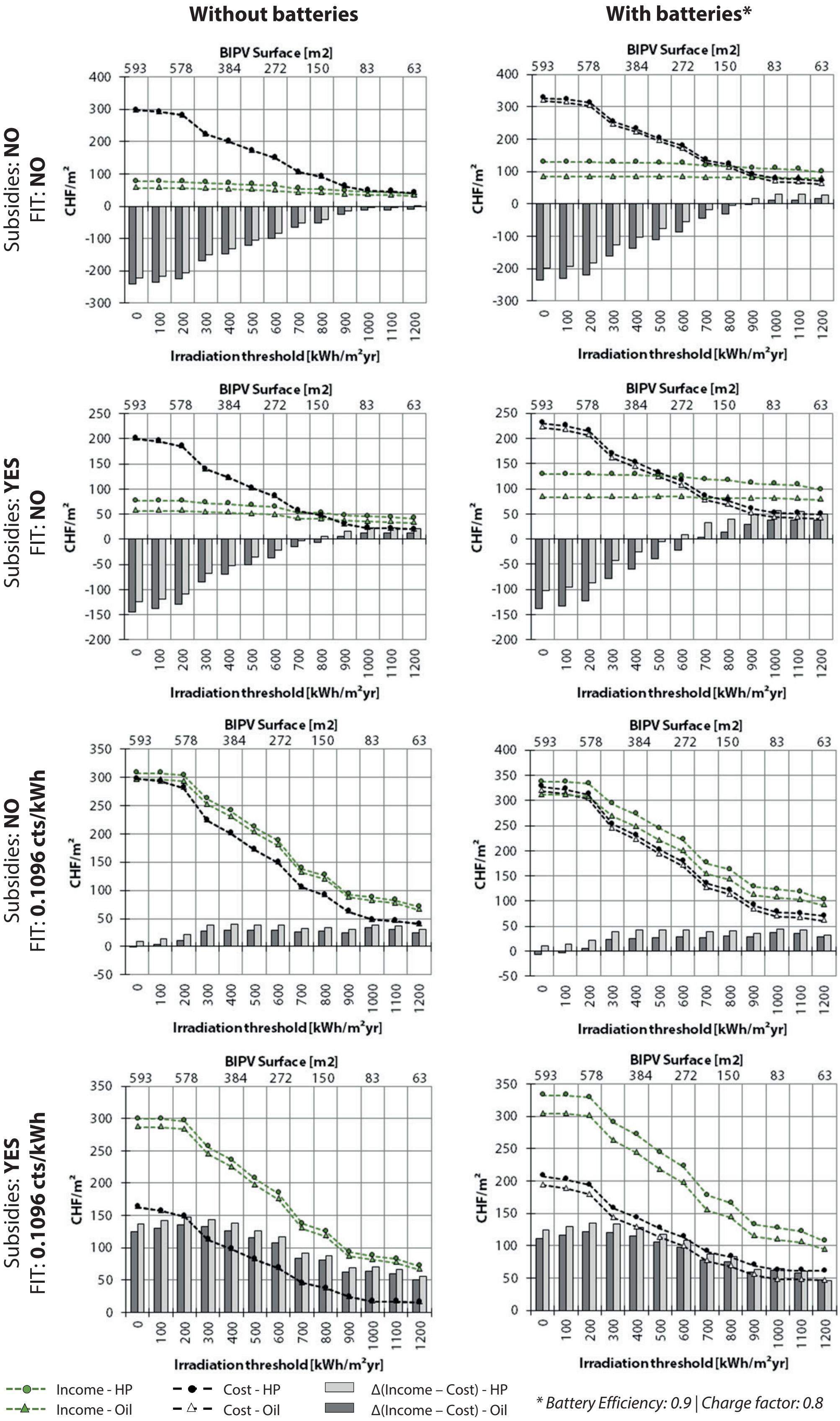


Figure 10-33. Simplified economic study for Archetype 1, S3-Tranformation scenario. Considering: Lifetime of BIPV installation: 25 years, and different options for investment subsidies and feed-in-tariffs.

10.4. Environmental impact data

The environmental impact values used in the LCA calculations in Chapter 7 are shown in Table 10-51 and Table 10-52 for construction materials (wall, roof, floor, windows), PV elements, facilities and HVAC systems.

Wall - Roof - Floor materials (service life of 60 years)	**CED**	**CEDnr**	**GWP**
For a 1 cm thickness	**[MJ/m²·y]**	**[MJ/m²·y]**	**[kgCO₂/m²·y]**
Adobe brick	0.99	0.50	0.03
Aluminium profile, uncoated	105.34	88.31	6.60
Cellular glass	0.97	0.72	0.04
Cellulose fibres	0.20	0.15	0.01
Cement mortar	0.65	0.57	0.08
Cement plaster	0.67	0.59	0.08
Ceramic roof tile	1.74	1.70	0.16
Concrete block	0.44	0.41	0.06
Concrete C 25/30	0.43	0.41	0.05
Concrete C 30/37	0.49	0.46	0.07
Copper sheet, uncoated	90.05	77.81	5.00
Cork board	2.09	1.00	0.05
Expanded perlite	0.57	0.55	0.03
Expanded polystyrene (100% recycled)	0.13	0.13	0.04
Expanded polystyrene (45% recycled)	0.60	0.60	0.06
Expanded polystyrene (EPS)	0.71	0.70	0.05
Extruded polystyrene (XPS)	0.67	0.66	0.10
Glass wool	0.50	0.46	0.02
Glulam timber, waterproof	3.95	1.04	0.07
Gypsum plasterboard	1.80	1.71	0.10
Light concrete block, expanded clay	1.68	1.63	0.12
Particle board V100	5.62	2.15	0.10
Particle board, cement bonded	1.03	0.40	0.05
Particle board, hard	9.50	3.06	0.18
Plywood / multiplex, waterproof	5.69	2.10	0.12
Polyurethane (PUR/PIR)	1.04	1.01	0.07
Reinforced concrete, C30/37, 100 kg/m3	3.84	1.77	0.15
Rockwool	0.57	0.51	0.04
Round Gravel	0.12	0.11	0.01
Sand	0.15	0.14	0.01
Sawn Timber, hardwood, air treated, raw	3.17	0.25	0.01
Sawn Timber, hardwood, air/kiln dried, planed	3.87	0.45	0.03
Sawn Timber, softwood, air dried, planed	2.24	0.30	0.01
Solid ceramic brick	0.68	0.62	0.06
Synthetic mortar	18.44	17.83	0.83
Synthetic plaster	2.00	1.95	0.07
Vapour barrier PE	21.40	20.69	1.12
OSB board	5.47	2.08	0.10
Asphalt carrier layer	1.74	1.72	0.05
Acrylic resin, water soluble	13.98	13.56	1.23
Alkyd resin, solvent soluble	25.08	23.52	1.53
Glass fibre reinforced polyamide	50.40	49.33	3.14
Glass fibre reinforced polyester	37.37	36.48	2.17
Plexiglas	43.04	42.64	3.41
Bitumen compound, hot	1.38	1.38	0.09
Bitumen	13.71	13.68	0.18

Table 10-51. Main characteristics of materials used for the Life-Cycle Analysis evaluation. Values are obtained from KBOB / Eco-bat database **[Favre et al. 2016; KBOB 2016]** for a building lifespan of 60 years. CED - cumulative energy demand, CEDnr - non-renewable cumulative energy demand, GWP - global warming potential.

Window components (service life of 20 years) **Per window area [m²]**	**CED** **[MJ/m²·y]**	**CEDnr** **[MJ/m²·y]**	**GWP** **[kgCO₂/m²·y]**
Double-glazing 2-IV-IR (argon)	44.46	42.35	3.03
Triple-glazing 3-IV-IR (argon)	86.71	82.24	5.54
Wooden window frame	95.17	46.96	3.02
Wood-metal window frame	129.36	79.55	5.45
Aluminium window frame	165.60	144.40	9.82
PVC window frame	131.21	125.76	7.57
Photovoltaic Installation (service life of 30 years) **Per element area [m²]**			
Mono - Wall	107.00	94.33	6.87
Mono - Flat Roof	109.00	96.33	7.10
Mono - Slopped Roof	104.00	92.33	6.70
Mono – Ecoinvent 2019 (data from research project PV2050) [Ballif 2015]	*81.00*	*71.00*	*6.16*
Poly - Wall	96.30	84.90	6.18
Poly - Flat Roof	98.10	86.70	6.39
Poly - Slopped Roof	93.90	83.10	6.03
Batteries (per kWh)	189.29	172.43	11.14
Facilities and HVAC (service life of 20 years) **Per floor area [m²]**			
Sanitary installation	4.93	4.66	0.30
Electrical installation	7.66	6.65	0.42
Air evacuation for kitchen or bathroom	2.02	1.92	0.12
Mechanical Ventilation - Steel channel	11.33	10.65	0.66
Mechanical Ventilation - HDPE channel	6.97	6.54	0.41
Heating - Production	1.036	0.966	0.059
Heating - Distribution	4.34	4.19	0.25
Indoor renovation (Kitchen + Bathroom)	4.93	4.66	0.30

Table 10-52. Main characteristics of materials used for the Life-Cycle Analysis evaluation. Values are obtained from KBOB / Eco-bat database **[Favre et al. 2016; KBOB 2016]** for a building lifespan of 60 years. CED - cumulative energy demand, CEDnr - non-renewable cumulative energy demand, GWP - global warming potential.

10.5. Global renovation cost

10.5.1. Archetype 1

Reference surfaces

Table 10-53 presents the reference surfaces for Archetype 1.

Reference area	*1*	*2*	*3*	*4*	*5*
Archetype 1	**m²**				
	Floor Area	**Façade Total**	**Façade Opaque**	**Windows**	**Roof**
	788.5	1002.4	636.8	85.1	280.5

Table 10-53. Reference areas for Archetype 1.

Renovation works without PV installation

Table 10-54 to Table 10-56 present the total and normalised cost of renovation for Archetype 1.

Archetype 1	**Total cost (CHF)**				**Ref.**
Element	**S0**	**S1**	**S2**	**S3**	**Area**
Roof (e.g. insulation…)	40'078	53'438	60'117	60'117	5
Façade (e.g. insulation…)	90'000	105'000	120'000	135'000	3
Windows substitution	74'207	137'813	137'813	137'813	4
Windows shading (e.g. store, blinds)	30'938	30'938	30'938	30'938	4
Exterior works (e.g. painting)	28'125	28'125	28'125	28'125	3
Scaffolding	45'000	45'000	45'000	45'000	2
Masonry general works	33'281	33'281	33'281	33'281	3
Wooden general works	38'438	38'438	38'438	38'438	3
Metal general works	24'680	24'680	24'680	164'531	1
Interior amenities (e.g. bathroom, kitchen)	106'406	106'406	106'406	106'406	1
Secondary fees	52'969	52'969	52'969	52'969	1
HVAC system renovation [cost | power]	- | 30 kW	22'500 | 30 kW	1'8000 | 24 kW	13'500 | 18 kW	-
Total [CHF]:	564'121	678'586	695'766	846'117	1

Table 10-54. Total cost of renovation works for Archetype 1.

Archetype 1	**Normalised cost (CHF/m² or CHF/kW)**				
Element	**S0**	**S1**	**S2**	**S3**	**Units**
Roof (e.g. insulation…)	143	214	214	214	CHF/m2
Façade (e.g. insulation…)	141	212	188	212	
Windows substitution	872	1'619	1'619	1'619	
Windows shading (e.g. store, blinds)	364	364	364	364	
Exterior works (e.g. painting)	44	44	44	44	
Scaffolding	45	45	45	45	
Masonry general works	52	52	52	52	
Wooden general works	60	60	60	60	
Metal general works	31	104	31	209	
Interior amenities (e.g. bathroom, kitchen)	135	135	135	135	
Secondary fees	67	67	67	67	
HVAC system renovation [cost | power]	750	750	750	750	CHF/kW
Total [CHF/m²]:	715	952	882	1'073	**CHF/m2**

Table 10-55. Normalised cost of renovation works for Archetype 1.

Renovation cost without PV installation	S0	S1	S2	S3	Units
Renovation cost (without subsidies)	564'121	678'586	695'766	846'117	**CHF**
Public aids (renovation): ProgBâtiment + Bonus NE	-	78'820	78'820	78'820	**CHF**
Renovation cost (incl. subsidies)	-	599'765	616'945	767'297	**CHF**

Table 10-56. Renovation cost without PV installation for Archetype 1. NE: Neuchâtel.

Global cost with PV installation

Table 10-57 to Table 10-59 present the global cost including PV installation for Archetype 1.

Global cost with PV | A-100% | HP - OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**564'121**	**622'261**	**652'059**	**895'604**	**CHF**
Total reduction (subsidies)	-	15%	16%	15%	%
PV surfaces	-	190	209	593	m^2
PV installed power	-	33	36	102	kWp
PV installation cost (without subsidies)	**-**	**56'772**	**76'116**	**204'643**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**299**	**364**	**345**	**CHF/m²**
Public aids (PV): RU	-	16'181	19'255	44'687	*CHF*
Public aids (PV): Tax Reduction	-	8'096	11'748	21'650	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**34'277**	**41'003**	**76'336**	**CHF**
Public aids (PV): total reduction	-	60%	54%	37%	%
PV installation cost (incl. public aids)	**-**	**22'495**	**35'114**	**128'307**	**CHF**
Normalised BIPV cost	**-**	**118**	**168**	**216**	**CHF/m²**

Table 10-57. Global cost with PV installation for Archetype 1 (A-100%, HP – OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**564'121**	**612'888**	**638'838**	**795'268**	**CHF**
Total reduction (subsidies)	-	14%	14%	12%	%
PV surfaces	-	77	77	77	m^2
PV installed power	-	13	13	13	kWp
PV installation cost (without subsidies)	**-**	**32'424**	**45'433**	**52'914**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**420**	**588**	**685**	**CHF/m²**
Public aids (PV): RU	-	7'639	9'239	9'239	*CHF*
Public aids (PV): Tax Reduction	-	5'099	7'739	9'141	*CHF*
Public aids (PV): Bonus NE	-	6'564	6'564	6'564	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**19'302**	**23'541**	**24'943**	**CHF**
Public aids (PV): total reduction	-	60%	52%	47%	%
PV installation cost (incl. public aids)	-	13'122	21'892	27'971	**CHF**
Normalised BIPV cost	-	170	284	362	**CHF/m²**
Battery capacity	-	84	84	84	kWh
Battery cost	-	20'992	20'992	20'992	CHF
PV installation cost (incl. public aids + batteries)		**34'114**	**42'884**	**48'963**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	**-**	**442**	**555**	**634**	**CHF/m²**

Table 10-58. Global cost with PV installation for Archetype 1 (B-Selection, OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | HP	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**564'121**	**620'270**	**657'308**	**813'511**	**CHF**
Total reduction (subsidies)	-	15%	15%	12%	%
PV surfaces	-	172	190	150	m²
PV installed power	-	29	33	26	kWp
PV installation cost (without subsidies)	**-**	**53'234**	**79'047**	**80'859**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**310**	**417**	**540**	**CHF/m²**
Public aids (PV): RU	-	15'014	18'028	14'911	*CHF*
Public aids (PV): Tax Reduction	-	7'715	10'656	9'733	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**32'730**	**38'684**	**34'644**	**CHF**
Public aids (PV): total reduction	-	61%	49%	43%	%
PV installation cost (incl. public aids)	**-**	**20'505**	**40'362**	**46'214**	**CHF**
Normalised BIPV cost	-	120	213	309	**CHF/m²**
Battery capacity	-	171.9	144	121.9	kWh
Battery cost	-	43296	36080	30832	CHF
PV installation cost (incl. public aids + batteries)		**63'801**	**76'442**	**77'046**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	**-**	**372**	**403**	**514**	**CHF/m²**

Table 10-59. Global cost with PV installation for Archetype 1 (B-Selection, HP). NE: Neuchâtel; RU (rétribution unique): unique grant.

10.5.2. Archetype 2

Reference surfaces

Table 10-53 presents the reference surfaces for Archetype 1.

Reference area	*1*	*2*	*3*	*4*	*5*
Archetype 2	**m²**				
	Floor Area	**Façade Total**	**Façade Opaque**	**Windows**	**Roof**
	847.2	1132.3	713.7	125.6	293.0

Table 10-60. Reference areas for Archetype 2.

Renovation works without PV installation

Table 10-61 to Table 10-63 present the total and normalised cost of renovation for Archetype 2.

Archetype 2	**Total cost (CHF)**				**Ref.**
Element	**S0**	**S1**	**S2**	**S3**	**Area**
Roof (e.g. insulation…)	41'745	52'182	55'660	69'576	5
Façade (e.g. insulation…)	152'863	194'553	208'450	222'347	3
Windows substitution	106'048	179'042	179'042	179'042	4
Windows shading (e.g. store, blinds)	44'212	44'212	44'212	44'212	4
Exterior works (e.g. painting)	31'268	31'268	31'268	31'268	3
Scaffolding	50'394	50'394	50'394	50'394	2
Masonry general works	37'000	37'000	37'000	37'000	3
Wooden general works	42'732	42'732	42'732	42'732	3
Metal general works	26'385	26'385	26'385	175'899	1
Interior amenities (e.g. bathroom, kitchen)	113'758	113'758	113'758	113'758	1
Secondary fees	56'628	56'628	56'628	56'628	1
HVAC system renovation [cost | power]	- | 32 kW	21'000 | 28 kW	18'750 | 25 kW	15'750 | 21 kW	-
Total [CHF]:	703'033	849'153	864'279	1'038'604	1

Table 10-61. Total cost of renovation works for Archetype 2.

Archetype 2	**Normalised cost (CHF/m² or CHF/kW)**				
Element	**S0**	**S1**	**S2**	**S3**	**Units**
Roof (e.g. insulation…)	142	237	190	237	CHF/m2
Façade (e.g. insulation…)	214	312	292	312	
Windows substitution	844	1'425	1'425	1'425	
Windows shading (e.g. store, blinds)	352	352	352	352	
Exterior works (e.g. painting)	44	44	44	44	
Scaffolding	45	45	45	45	
Masonry general works	52	52	52	52	
Wooden general works	60	60	60	60	
Metal general works	31	104	31	208	
Interior amenities (e.g. bathroom, kitchen)	134	134	134	134	
Secondary fees	67	67	67	67	
HVAC system renovation [cost | power]	750	750	750	750	CHF/kW
Total [CHF/m²]:	830	1'104	1'020	1'226	**CHF/m2**

Table 10-62. Normalised cost of renovation works for Archetype 2.

Renovation cost without PV installation	S0	S1	S2	S3	Units
Renovation cost (without subsidies)	703'033	849'153	864'279	1'038'604	**CHF**
Public aids (renovation): ProgBâtiment + Bonus NE	-	84'875	84'875	88'700	**CHF**
Renovation cost (incl. subsidies)	-	764'279	779'404	949'905	**CHF**

Table 10-63. Renovation cost without PV installation for Archetype 2. NE: Neuchâtel.

Global cost with PV installation

Table 10-64 to Table 10-66 present the global cost including PV installation for Archetype 2.

Global cost with PV | A-100% | HP - OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**703'033**	**782'350**	**797'476**	**1'129'142**	**CHF**
Total reduction (subsidies)	-	13%	13%	13%	%
PV surfaces	-	147	147	821	m^2
PV installed power	-	25	25	141	kWp
PV installation cost (without subsidies)	**-**	**48'323**	**48'323**	**265'650**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**329**	**329**	**324**	**CHF/m²**
Public aids (PV): RU	-	13'095	13'095	57'240	*CHF*
Public aids (PV): Tax Reduction	-	7'156	7'156	19'173	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**30'252**	**30'252**	**86'413**	**CHF**
Public aids (PV): total reduction	-	63%	63%	33%	%
PV installation cost (incl. public aids)	**-**	**18'072**	**18'072**	**179'237**	**CHF**
Normalised BIPV cost	**-**	**123**	**123**	**218**	**CHF/m²**

Table 10-64. Global cost with PV installation for Archetype 2 (A-100%, HP – OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**703'033**	**776'171**	**791'296**	**973'840**	**CHF**
Total reduction (subsidies)	-	11%	11%	10%	%
PV surfaces	-	59	59	59	m^2
PV installed power	-	10	10	10	kWp
PV installation cost (without subsidies)	**-**	**27'527**	**27'527**	**44'577**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**466**	**466**	**754**	**CHF/m²**
Public aids (PV): RU	-	6'222	6'222	7'822	*CHF*
Public aids (PV): Tax Reduction	-	4'388	4'388	7'796	*CHF*
Public aids (PV): Bonus NE	-	5'024	5'024	5'024	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**15'635**	**15'635**	**20'642**	**CHF**
Public aids (PV): total reduction	-	57%	57%	46%	%
PV installation cost (incl. public aids)	**-**	**11'892**	**11'892**	**23'936**	**CHF**
Normalised BIPV cost	-	201	201	405	**CHF/m²**
Battery capacity	-	71	71	70	kWh
Battery cost	-	20'493	20'493	20'493	CHF
PV installation cost (incl. public aids + batteries)		**32'385**	**32'385**	**44'429**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	**-**	**548**	**548**	**752**	**CHF/m²**

Table 10-65. Global cost with PV installation for Archetype 2 (B-Selection, OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | HP	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**703'033**	**782'319**	**797'445**	**1'046'599**	**CHF**
Total reduction (subsidies)	-	13%	13%	12%	%
PV surfaces	-	147	147	375	m²
PV installed power	-	25	25	64	kWp
PV installation cost (without subsidies)	**-**	**48'262**	**48'262**	**151'227**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**329**	**329**	**403**	**CHF/m²**
Public aids (PV): RU	-	13'072	13'072	29'851	*CHF*
Public aids (PV): Tax Reduction	-	7'149	7'149	14'682	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**30'221**	**30'221**	**54'533**	**CHF**
Public aids (PV): total reduction	-	63%	63%	36%	%
PV installation cost (incl. public aids)	**-**	**18'041**	**18'041**	**96'694**	**CHF**
Normalised BIPV cost	**-**	**123**	**123**	**258**	**CHF/m²**
Battery capacity	-	120	114	100	kWh
Battery cost	-	34914	33396	28842	CHF
PV installation cost (incl. public aids + batteries)		**52'955**	**51'437**	**125'536**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	**-**	**361**	**351**	**335**	**CHF/m²**

Table 10-66. Global cost with PV installation for Archetype 2 (B-Selection, HP). NE: Neuchâtel; RU (rétribution unique): unique grant.

10.5.3. Archetype 3

Reference surfaces

Table 10-67 presents the reference surfaces for Archetype 3.

Reference area	*1*	*2*	*3*	*4*	*5*
	m²				
Archetype 3	**Floor Area**	**Façade Total**	**Façade Opaque**	**Windows**	**Roof**
	4415.5	3331.5	1700.1	883.9	747.5

Table 10-67. Reference areas for Archetype 3.

Renovation works without PV installation

Table 10-68 to Table 10-70 present the total and normalised cost of renovation for Archetype 3.

Archetype 3	**Total cost (CHF)**				**Ref.**
Element	**S0**	**S1**	**S2**	**S3**	**Area**
Roof (e.g. insulation…)	118'700	142'440	158'267	174'093	5
Façade (e.g. insulation…)	370'696	474'491	444'835	563'458	3
Windows substitution	288'432	486'963	486'963	486'963	4
Windows shading (e.g. store, blinds)	120'250	120'250	120'250	120'250	4
Exterior works (e.g. painting)	66'725	66'725	66'725	66'725	3
Scaffolding	126'393	126'393	126'393	126'393	2
Masonry general works	78'958	78'958	78'958	78'958	3
Wooden general works	91'191	91'191	91'191	91'191	3
Metal general works	95'822	95'822	95'822	638'816	1
Interior amenities (e.g. bathroom, kitchen)	413'137	413'137	413'137	413'137	1
Secondary fees	205'659	205'659	205'659	205'659	1
HVAC system renovation [cost | power]	- | 165 kW	110'250 | 147 kW	102'750 | 137 kW	87'750 | 117 kW	-
Total [CHF]:	1'975'963	2'412'279	2'390'950	3'053'393	1

Table 10-68. Total cost of renovation works for Archetype 3.

Archetype 3	**Normalised cost (CHF/m² or CHF/kW)**				
Element	**S0**	**S1**	**S2**	**S3**	**Units**
Roof (e.g. insulation…)	159	233	212	233	CHF/m2
Façade (e.g. insulation…)	218	331	262	331	
Windows substitution	326	551	551	551	
Windows shading (e.g. store, blinds)	136	136	136	136	
Exterior works (e.g. painting)	39	39	39	39	
Scaffolding	38	38	38	38	
Masonry general works	46	46	46	46	
Wooden general works	54	54	54	54	
Metal general works	22	22	22	145	
Interior amenities (e.g. bathroom, kitchen)	94	94	94	94	
Secondary fees	47	47	47	47	
HVAC system renovation [cost | power]	750	750	750	750	CHF/kW
Total [CHF/m²]:	448	549	541	692	**CHF/m2**

Table 10-69. Normalised cost of renovation works for Archetype 3.

Renovation cost without PV installation	S0	S1	S2	S3	Units
Renovation cost (without subsidies)	1'975'963	2'412'279	2'390'950	3'053'393	**CHF**
Public aids (renovation): ProgBâtiment + Bonus NE	-	482'398	548'631	548'631	**CHF**
Renovation cost (incl. subsidies)	-	1'929'881	1'842'319	2'504'762	**CHF**

Table 10-70. Renovation cost without PV installation for Archetype 3. NE: Neuchâtel.

Global cost with PV installation

Table 10-71 to Table 10-73 present the global cost including PV installation for Archetype 3.

Global cost with PV | A-100% | HP - OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'975'963**	**1'993'260**	**2'126'025**	**2'848'579**	**CHF**
Total reduction (subsidies)	-	21%	24%	19%	%
PV surfaces	-	462	1'526	1'845	m^2
PV installed power	-	79	262	316	kWp
PV installation cost (without subsidies)	**-**	**123'853**	**404'089**	**475'317**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**268**	**265**	**258**	**CHF/m²**
Public aids (PV): RU	-	31'689	95'191	113'629	*CHF*
Public aids (PV): Tax Reduction	-	18'786	15'193	7'871	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**60'475**	**120'384**	**131'501**	**CHF**
Public aids (PV): total reduction	-	49%	30%	28%	%
PV installation cost (incl. public aids)	**-**	**63'379**	**283'706**	**343'817**	**CHF**
Normalised BIPV cost	**-**	**137**	**186**	**186**	**CHF/m²**

Table 10-71. Global cost with PV installation for Archetype 3 (A-100%, HP – OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant

Global cost with PV | B-Selection | OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'975'963**	**1'998'721**	**1'943'657**	**2'614'595**	**CHF**
Total reduction (subsidies)	-	21%	24%	19%	%
PV surfaces	-	358	427	463	m^2
PV installed power	-	61	73	79	kWp
PV installation cost (without subsidies)	**-**	**126'521**	**161'720**	**172'060**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**354**	**379**	**371**	**CHF/m²**
Public aids (PV): RU	-	28'512	32'009	34'050	*CHF*
Public aids (PV): Tax Reduction	-	19'169	18'373	18'177	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**57'681**	**60'382**	**62'227**	**CHF**
Public aids (PV): total reduction	-	46%	37%	36%	%
PV installation cost (incl. public aids)	**-**	**68'840**	**101'337**	**109'833**	**CHF**
Normalised BIPV cost	**-**	**193**	**237**	**237**	**CHF/m²**
Battery capacity	-	217	217	217	kWh
Battery cost	-	112'176	112'176	112'176	CHF
PV installation cost (incl. public aids + batteries)		**181'016**	**213'513**	**222'009**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	**-**	**506**	**500**	**479**	**CHF/m²**

Table 10-72. Global cost with PV installation for Archetype 3 (B-Selection, OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | HP	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'975'963**	**1'998'721**	**2'054'259**	**2'736'990**	**CHF**
Total reduction (subsidies)	-	21%	24%	19%	%
PV surfaces	-	358	1046	1151	m²
PV installed power	-	61	179	197	kWp
PV installation cost (without subsidies)	**-**	**126'521**	**311'237**	**336'997**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**354**	**298**	**293**	**CHF/m²**
Public aids (PV): RU	-	*28'512*	*68'820*	*74'758*	*CHF*
Public aids (PV): Tax Reduction	-	*19'169*	*20'478*	*20'011*	*CHF*
Public aids (PV): Bonus NE	-	*10'000*	*10'000*	*10'000*	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**57'681**	**99'298**	**104'769**	**CHF**
Public aids (PV): total reduction	-	46%	32%	31%	%
PV installation cost (incl. public aids)	**-**	**68'840**	**211'940**	**232'228**	**CHF**
Normalised BIPV cost	-	**193**	**203**	**202**	**CHF/m²**
Battery capacity	-	385	365	315	kWh
Battery cost	-	112176	112176	112176	CHF
PV installation cost (incl. public aids + batteries)		**181'016**	**324'116**	**344'404**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	-	**506**	**310**	**299**	**CHF/m²**

Table 10-73. Global cost with PV installation for Archetype 3 (B-Selection, HP). NE: Neuchâtel; RU (rétribution unique): unique grant.

10.5.4. Archetype 4

Reference surfaces

Table 10-74 presents the reference surfaces for Archetype 4.

Reference area	*1*	*2*	*3*	*4*	*5*
Archetype 4	**m²**				
	Floor Area	**Façade Total**	**Façade Opaque**	**Windows**	**Roof**
	5263.0	3677.0	2201.8	972.2	503.0

Table 10-74. Reference areas for Archetype 4.

Renovation works without PV installation

Table 10-75 to Table 10-77 present the total and normalised cost of renovation for Archetype 4.

Archetype 4	**Total cost (CHF)**				**Ref.**
Element	**S0**	**S1**	**S2**	**S3**	**Area**
Roof (e.g. insulation…)	68'077	85'096	90'769	102'116	5
Façade (e.g. insulation…)	271'032	379'445	379'445	487'858	3
Windows substitution	258'610	480'275	480'275	480'275	4
Windows shading (e.g. store, blinds)	107'817	107'817	107'817	107'817	4
Exterior works (e.g. painting)	81'310	81'310	81'310	81'310	3
Scaffolding	135'707	135'707	135'707	135'707	2
Masonry general works	96'216	96'216	96'216	96'216	3
Wooden general works	111'123	111'123	111'123	111'123	3
Metal general works	102'410	102'410	102'410	682'734	1
Interior amenities (e.g. bathroom, kitchen)	441'540	441'540	441'540	441'540	1
Secondary fees	219'798	219'798	219'798	219'798	1
HVAC system renovation [cost | power]	- | 194 kW	98'250 | 131 kW	87'000 | 116 kW	77'250 | 103 kW	-
Total [CHF]:	1'893'640	2'338'987	2'333'411	3'023'744	1

Table 10-75. Total cost of renovation works for Archetype 4.

Archetype 4	**Normalised cost (CHF/m² or CHF/kW)**				
Element	**S0**	**S1**	**S2**	**S3**	**Units**
Roof (e.g. insulation…)	135	203	180	203	CHF/m2
Façade (e.g. insulation…)	123	222	172	222	
Windows substitution	266	494	494	494	
Windows shading (e.g. store, blinds)	111	111	111	111	
Exterior works (e.g. painting)	37	37	37	37	
Scaffolding	37	37	37	37	
Masonry general works	44	44	44	44	
Wooden general works	50	50	50	50	
Metal general works	19	19	19	130	
Interior amenities (e.g. bathroom, kitchen)	84	84	84	84	
Secondary fees	42	42	42	42	
HVAC system renovation [cost | power]	750	750	750	750	CHF/kW
Total [CHF/m²]:	360	450	443	575	**CHF/m2**

Table 10-76. Normalised cost of renovation works for Archetype 4.

Renovation cost without PV installation	S0	S1	S2	S3	Units
Renovation cost (without subsidies)	1'893'640	2'338'987	2'333'411	3'023'744	**CHF**
Public aids (renovation): ProgBâtiment + Bonus NE	-	556'410	632'805	632'805	**CHF**
Renovation cost (incl. subsidies)	-	1'782'577	1'700'605	2'390'938	**CHF**

Table 10-77. Renovation cost without PV installation for Archetype 4. NE: Neuchâtel.

Global cost with PV installation

Table 10-78 to Table 10-80 present the global cost including PV installation for Archetype 4.

Global cost with PV | A-100% | HP - OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'893'640**	**1'906'516**	**1'949'563**	**2'806'175**	**CHF**
Total reduction (subsidies)	-	25%	27%	22%	%
PV surfaces	-	565	1'196	2'192	m^2
PV installed power	-	97	205	376	kWp
PV installation cost (without subsidies)	**-**	**194'943**	**348'905**	**566'731**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**345**	**292**	**259**	**CHF/m²**
Public aids (PV): RU	-	40'623	77'094	134'663	*CHF*
Public aids (PV): Tax Reduction	-	20'381	12'853	6'832	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	-	71'004	99'947	151'495	CHF
Public aids (PV): total reduction	-	36%	29%	27%	%
PV installation cost (incl. public aids)	**-**	**123'939**	**248'958**	**415'236**	**CHF**
Normalised BIPV cost	**-**	**219**	**208**	**189**	**CHF/m²**

Table 10-78. Global cost with PV installation for Archetype 4 (A-100%, HP – OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'893'640**	**1'902'166**	**1'814'302**	**2'495'400**	**CHF**
Total reduction (subsidies)	-	25%	28%	22%	%
PV surfaces	-	562	565	566	m^2
PV installed power	-	96	97	97	kWp
PV installation cost (without subsidies)	**-**	**191'394**	**186'488**	**177'478**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**341**	**330**	**313**	**CHF/m²**
Public aids (PV): RU	-	40'730	40'799	40'399	*CHF*
Public aids (PV): Tax Reduction	-	21'076	21'993	22'617	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**71'805**	**72'792**	**73'016**	**CHF**
Public aids (PV): total reduction	-	38%	39%	41%	%
PV installation cost (incl. public aids)	**-**	**119'589**	**113'696**	**104'462**	**CHF**
Normalised BIPV cost	**-**	**213**	**201**	**184**	**CHF/m²**
Battery capacity	-	498	498	485	kWh
Battery cost	-	143'451	122'016	120'704	CHF
PV installation cost (incl. public aids + batteries)		**263'040**	**235'712**	**225'166**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	**-**	**468**	**417**	**398**	**CHF/m²**

Table 10-79. Global cost with PV installation for Archetype 4 (B-Selection, OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | HP	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'893'640**	**1'891'842**	**1'912'885**	**2'560'038**	**CHF**
Total reduction (subsidies)	-	25%	28%	22%	%
PV surfaces	-	523	1131	942	m²
PV installed power	-	90	194	161	kWp
PV installation cost (without subsidies)	**-**	**179'127**	**317'813**	**263'256**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**343**	**281**	**280**	**CHF/m²**
Public aids (PV): RU	-	38'606	72'720	61'330	*CHF*
Public aids (PV): Tax Reduction	-	21'256	22'813	22'827	*CHF*
Public aids (PV): Bonus NE	-	10'000	10'000	10'000	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**69'862**	**105'533**	**94'156**	**CHF**
Public aids (PV): total reduction	-	39%	33%	36%	%
PV installation cost (incl. public aids)	**-**	**109'265**	**212'280**	**169'099**	**CHF**
Normalised BIPV cost	-	209	188	180	**CHF/m²**
Battery capacity	-	701	665	653	kWh
Battery cost	-	174496	165968	162688	CHF
PV installation cost (incl. public aids + batteries)		**283'761**	**378'248**	**331'787**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	**-**	**543**	**335**	**352**	**CHF/m²**

Table 10-80. Global cost with PV installation for Archetype 5 (B-Selection, HP). NE: Neuchâtel; RU (rétribution unique): unique grant.

10.5.5. Archetype 5

Reference surfaces

Table 10-81 presents the reference surfaces for Archetype 5.

Reference area	*1*	*2*	*3*	*4*	*5*
	m²				
Archetype 5	**Floor Area**	**Façade Total**	**Façade Opaque**	**Windows**	**Roof**
	4417.1	3064.5	1587.8	514.3	503.0

Table 10-81. Reference areas for Archetype 5.

Renovation works without PV installation

Table 10-82 to Table 10-84 present the total and normalised cost of renovation for Archetype 5.

Archetype 5	**Total cost (CHF)**				**Ref.**
Element	**S0**	**S1**	**S2**	**S3**	**Area**
Roof (e.g. insulation…)	45'385	68'077	73'750	124'808	5
Façade (e.g. insulation…)	0	364'816	336'753	420'942	3
Windows substitution	297'679	502'575	502'575	502'575	4
Windows shading (e.g. store, blinds)	124'105	124'105	124'105	124'105	4
Exterior works (e.g. painting)	63'141	63'141	63'141	63'141	3
Scaffolding	17'806	17'806	118'707	118'707	2
Masonry general works	74'717	74'717	74'717	74'717	3
Wooden general works	86'293	86'293	86'293	86'293	3
Metal general works	95'838	95'838	95'838	638'917	1
Interior amenities (e.g. bathroom, kitchen)	413'203	413'203	413'203	413'203	1
Secondary fees	205'691	205'691	205'691	205'691	1
HVAC system renovation [cost | power]	- | 194 kW	98'250 | 131 kW	87'000 | 116 kW	77'250 | 103 kW	-
Total [CHF]:	**1'423'858**	**2'114'512**	**2'181'773**	**2'850'348**	1

Table 10-82. Total cost of renovation works for Archetype 5.

Archetype 5	**Normalised cost (CHF/m² or CHF/kW)**				
Element	**S0**	**S1**	**S2**	**S3**	**Units**
Roof (e.g. insulation…)	90	248	147	248	CHF/m2
Façade (e.g. insulation…)	0	265	212	265	
Windows substitution	579	977	977	977	
Windows shading (e.g. store, blinds)	241	241	241	241	
Exterior works (e.g. painting)	40	40	40	40	
Scaffolding	6	39	39	39	
Masonry general works	47	47	47	47	
Wooden general works	54	54	54	54	
Metal general works	22	22	22	145	
Interior amenities (e.g. bathroom, kitchen)	94	94	94	94	
Secondary fees	47	47	47	47	
HVAC system renovation [cost | power]	750	750	750	750	CHF/kW
Total [CHF/m²]:	**322**	**505**	**494**	**645**	**CHF/m2**

Table 10-83. Normalised cost of renovation works for Archetype 5.

Renovation cost without PV installation	S0	S1	S2	S3	Units
Renovation cost (without subsidies)	**1'423'858**	**2'114'512**	**2'181'773**	**2'850'348**	**CHF**
Public aids (renovation): ProgBâtiment + Bonus NE	**-**	**429'030**	**429'030**	**429'030**	**CHF**
Renovation cost (incl. subsidies)	**-**	**1'685'482**	**1'752'743**	**2'421'318**	**CHF**

Table 10-84. Renovation cost without PV installation for Archetype 5. NE: Neuchâtel.

Global cost with PV installation

Table 10-85 to Table 10-87 present the global cost including PV installation for Archetype 5

Global cost with PV | A-100% | HP - OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'423'858**	**1'763'895**	**2'105'188**	**2'773'764**	**CHF**
Total reduction (subsidies)	-	22%	22%	18%	%
PV surfaces	-	941	2'200	2'200	m^2
PV installed power	-	161	377	377	kWp
PV installation cost (without subsidies)	**-**	**160'609**	**514'485**	**514'485**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**171**	**234**	**234**	**CHF/m²**
Public aids (PV): RU	-	*59'609*	*137'560*	*137'560*	*CHF*
Public aids (PV): Tax Reduction	-	*12'587*	*14'480*	*14'480*	*CHF*
Public aids (PV): Bonus NE	-	*10'000*	*10'000*	*10'000*	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**82'196**	**162'040**	**162'040**	**CHF**
Public aids (PV): total reduction	-	51%	31%	31%	%
PV installation cost (incl. public aids)	**-**	**78'413**	**352'445**	**352'445**	**CHF**
Normalised BIPV cost	-	**83**	**160**	**160**	**CHF/m²**

Table 10-85. Global cost with PV installation for Archetype 5 (A-100%, HP – OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | OIL/GAS	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'423'858**	**1'763'642**	**1'937'344**	**2'605'920**	**CHF**
Total reduction (subsidies)	-	22%	22%	17%	%
PV surfaces	-	937	999	999	m^2
PV installed power	-	161	171	171	kWp
PV installation cost (without subsidies)	**-**	**160'109**	**286'892**	**286'892**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**171**	**287**	**287**	**CHF/m²**
Public aids (PV): RU	-	*59'357*	*68'140*	*68'140*	*CHF*
Public aids (PV): Tax Reduction	-	*12'591*	*24'150*	*24'150*	*CHF*
Public aids (PV): Bonus NE	-	*10'000*	*10'000*	*10'000*	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**81'949**	**102'290**	**102'290**	**CHF**
Public aids (PV): total reduction	-	51%	36%	36%	%
PV installation cost (incl. public aids)	**-**	**78'160**	**184'602**	**184'602**	**CHF**
Normalised BIPV cost	-	**83**	**185**	**185**	**CHF/m²**
Battery capacity	-	367	367	367	kWh
Battery cost	-	91'840	91'840	91'840	CHF
PV installation cost (incl. public aids + batteries)		**170'000**	**276'442**	**276'442**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	-	**181**	**277**	**277**	**CHF/m²**

Table 10-86. Global cost with PV installation for Archetype 5 (B-Selection, OIL/GAS). NE: Neuchâtel; RU (rétribution unique): unique grant.

Global cost with PV | B-Selection | HP	S0	S1	S2	S3	Units
Global cost of the renovation (incl. PV + subsidies)	**1'423'858**	**1'763'642**	**1'938'265**	**2'606'841**	**CHF**
Total reduction (subsidies)	-	22%	21%	17%	%
PV surfaces	-	937	999	999	m^2
PV installed power	-	161	171	171	kWp
PV installation cost (without subsidies)	**-**	**160'109**	**286'892**	**286'892**	**CHF**
Normalised BIPV cost (without subsidies)	**-**	**171**	**287**	**287**	**CHF/m²**
Public aids (PV): RU	-	*59'357*	*68'140*	*68'140*	*CHF*
Public aids (PV): Tax Reduction	-	*12'591*	*23'229*	*23'229*	*CHF*
Public aids (PV): Bonus NE	-	*10'000*	*10'000*	*10'000*	*CHF*
Public aids (PV): RU + Tax Reduction + Bonus NE	**-**	**81'949**	**101'369**	**101'369**	**CHF**
Public aids (PV): total reduction	-	51%	35%	35%	%
PV installation cost (incl. public aids)	**-**	**78'160**	**185'523**	**185'523**	**CHF**
Normalised BIPV cost	-	**83**	**186**	**186**	**CHF/m²**
Battery capacity	-	663	590	532	kWh
Battery cost	-	165312	146944	132512	CHF
PV installation cost (incl. public aids + batteries)		**243'472**	**332'467**	**318'035**	**CHF**
Normalised BIPV cost (incl. public aids + batteries)	-	**260**	**333**	**318**	**CHF/m²**

Table 10-87. Global cost with PV installation for Archetype 5 (B-Selection, HP). NE: Neuchâtel; RU (rétribution unique): unique grant.

10.6. Definitions and formulas

10.6.1. Photovoltaic performance

Levelized cost of energy (LCOE): (or cost of electricity) it is the sum of the costs to build and operate a power-generating asset over its lifetime (30 years) divided by the total electricity produced.

$$\text{LCOE} = \frac{\text{total cost over lifetime}}{\text{total electricity produced over lifetime}} = \frac{It + \sum_{t=1}^{n} Mt}{\sum_{t=1}^{n} EPV}$$

Where:
LCOE: *Levelized cost of energy [CHF/kWh$_{e\text{-}pv}$]*
It: Investment (in the year t) [CHF]
Mt: Operation and maintenance cost (in the year t) [CHF]
EPV: Annual electricity production (considering 0.8%/year of efficiency losses) [kWh$_{e\text{-}pv}$/year]
n: Expected lifetime [years] – (30 years)

Primary Energy Factor (non-renewable) ($NRPEF_{PV}$): parameter connecting primary (PE) and final energy (FE). It indicates how much primary energy was used to generate a unit of electricity, considering the whole lifetime (30 years).

$$NRPEF_{PV} = \frac{\text{total NRPE consummed}}{\text{total electricity produced over lifetime}} = \frac{NRPE}{\sum_{t=1}^{n} EPVt}$$

Where:
NRPEF: *(Non-renewable) Primary Energy Factor [kWh$_{NRPE}$/kWh$_{e\text{-}pv}$]*
NRPE: Non-renewable primary energy consumed [kWh$_{NRPE}$] [KBOB 2016]
EPV: Annual electricity production (considering 0.8%/year of efficiency losses) [kWh$_{e\text{-}pv}$/year]
n: Expected lifetime [years] – (30 years)

Carbon Content Factor (CCF_{PV}): parameter connecting GHG emissions and final energy (FE). It indicates how much GHG emissions was emitted to generate a unit of electricity, considering the whole lifetime (30 years).

$$CCF_{PV} = \frac{\text{Total GHG emitted}}{\text{Total electricity produced}} = \frac{GHG}{\sum_{t=1}^{n} EPVt}$$

Where:
CCF_{PV}: *Carbon Content Factor [kg$CO_{2\text{-}eq}$/kWh$_{e\text{-}pv}$]*
GHG: Greenhouse gas emitted [kg$CO_{2\text{-}eq}$] [KBOB 2016]
EPV: Annual electricity production (considering 0.8%/year of efficiency losses) [kWh$_{e\text{-}pv}$/year]
n: Expected lifetime [years] – (30 years)

Energy Payback Time ($EPBT_{PV}$): required time for a complete photovoltaic system (modules, cables, electronic equipment) to compensate the primary energy consumed for its production and operation, considering the whole lifetime (30 years).

$$EPBT_{PV} = \frac{\text{Total NRPE consummed}}{\text{Annual NRPE avoid due to PV production}} = \frac{NRPE}{EPV \cdot PEF_{Grid}}$$

Where:
$EPBT_{PV}$: *Energy Payback Time [years]*
NRPE: Non-renewable primary energy consumed [kWh$_{NRPE}$] [KBOB 2016]
EPV: Annual electricity production [kWh$_{e\text{-}pv}$/year]
PEF_{Grid}: Non-renewable Primary Energy Factor of Swiss grid [2.52 kWh$_{NRE}$ /kWh$_{e\text{-}pv}$] [KBOB 2016]

GHG Emissions Payback Time ($GPBT_{PV}$): required time for a complete photovoltaic system (modules, cables, electronic equipment) to compensate the GHG emitted for its production and operation, considering the whole lifetime (30 years).

$$GPBT_{PV} = \frac{\text{Total GHG emitted}}{\text{Annual GHG emissions avoided due to PV production}} = \frac{GHG}{EPV \cdot CCF_{Grid}}$$

Where:
$GPBT_{PV}$: GHG Emissions Payback Time [years]
GHG: Total GHG emitted [$kgCO_{2\text{-}eq}$] [KBOB 2016]
EPV: Annual electricity production [$kWh_{e\text{-}pv}$/year]
CCF_{Grid}: Carbon Content Factor of Swiss grid [0.102 $kgCO_{2\text{-}eq}/kWh_{e\text{-}pv}$] [KBOB 2016]

10.6.2. Operational energy balance

Final energy consumption (FE): calculated through energy simulation software (with hourly time-step); it is the final energy consumption for appliances, lighting, ventilation, heating and domestic hot water.

Power needed: it is the maximum power required for the HVAC system, sized using the annual energy consumption.

Self-consumption rate (SC): percentage of electricity produced by the BIPV system that is consumed directly by the building, showing the level of utilisation on-site of the electricity produced.

$$SC = \frac{\text{PV electricity consumed by the building}}{\text{Annual electricity production}} = \frac{\sum_{t=1}^{n} CPVt}{EPV}$$

Where:
SC: Self-consumption rate [%]
CPV: Hourly PV electricity consumed directly by the building [$kWh_{e\text{-}pv}$]
EPV: Annual electricity production [$kWh_{e\text{-}pv}$/year]
n: Simulation period [hours] – (8760 hours)

Self-sufficiency rate (SS): ratio between the photovoltaic electricity consumed on-site and the total electricity needs. Shows the real coverage of the demand for electricity on the basis of self-consumption, equivalent to the level of energy independence of the building.

$$SS = 1 - \frac{\text{Electricity purchased}}{\text{Annal electricity needs}} = \frac{\text{PV electricity consumed by the building}}{\text{Anual electricity needs}} = \frac{\sum_{t=1}^{n} CPVt}{EN}$$

Where:
SS: Self- sufficiency rate [%]
CPV: Hourly PV electricity consumed directly by the building [$kWh_{e\text{-}pv}$]
EN: Annual electricity needs [$kWh_{e\text{-}pv}$/year]
n: Simulation period [hours] – (8760 hours)

PV electricity self-consumed (PVSC): total PV electricity self-consumed by the building.

$$PVSC = SC \cdot EPV$$

Where:
PVSC: PV electricity self-consumed [$kWh_{e\text{-}pv}/m^2\cdot$year]
SC: Self-consumption rate [%]
EPV: Annual electricity production [$kWh_{e\text{-}pv}$/year]

PV electricity injected (PVI): total PV electricity energy (overproduced) injected into the grid.

$$PVSC = (1\text{-}SC) \cdot EPV$$

Where:
PVI: *PV electricity injected [$kWh_{e\text{-}pv}/m^2 \cdot year$]*
SC: Self-consumption rate [%]
EPV: Annual electricity production [$kWh_{e\text{-}pv}$/year]

Cumulative Energy Demand (CEDnr-op): non-renewable primary energy consumed for the operation of the building including appliances, lighting, ventilation, heating and domestic hot water.

$$\text{CEDnr-op} = PEF \cdot \sum_{t=1}^{n} FEt$$

Where:
CEDnr-op: Cumulative Energy Demand (operational) [$kWh_{NRE}/m^2 \cdot year$]
FE: Final energy consumption per type of energy source (electricity, oil or natural gas) [kWh/year]
PEF: Non-renewable Primary Energy Factor (Electricity: 2.52 kWh_{NRE} /$kWh_{e\text{-}pv}$, Oil: 1.23 kWh_{NRE} /kWh_{oil}, Natural gas: 1.06 kWh_{NRE} /kWh_{gas}) [KBOB 2016]
n: Life-cycle period considered [years] – (60 years)

Global Warming Potential (GWP-op): GHG emissions related to the operation of the building including appliances, lighting, ventilation, heating and domestic hot water.

$$\text{GWP-op} = CCF \cdot \sum_{t=1}^{n} FEt$$

Where:
GWP-op: Global Warming Potential (operational) [$kgCO_{2\text{-}eq}/m^2 \cdot year$]
FE: Final energy consumption per type of energy source (electricity, oil or natural gas) [kWh/year]
CCF: Carbon Content Factor (Electricity: 0.102 $kgCO_{2\text{-}eq}/kWh_{e\text{-}pv}$, Oil: 0.301 $kgCO_{2\text{-}eq}/kWh_{oil}$, Natural gas: 0.228 $kgCO_{2\text{-}eq}/kWh_{gas}$) [KBOB 2016]
n: Life-cycle period considered [years] – (60 years)

10.6.3. Life-Cycle Analysis (LCA)

Cumulative Energy Demand (CEDnr): non-renewable primary energy consumed for the operation of the building and the construction materials (including the BIPV installation).

$$\text{CEDnr} = \text{EE} + \text{PEF} \cdot \sum_{t=1}^{n} FEt$$

Where:

CEDnr: *Cumulative Energy Demand (operational + materials) [$kWh_{NRE}/m^2 \cdot year$]*

EE: Non-renewable primary energy consumed due to the used materials (embodied energy).

FE: Final energy consumption per type of energy source (electricity, oil or natural gas) [kWh]

PEF: Non-renewable Primary Energy Factor (Electricity: 2.52 kWh_{NRE} /$kWh_{e\text{-}pv}$, Oil: 1.23 kWh_{NRE} /kWh_{oil}, Natural gas: 1.06 kWh_{NRE} /kWh_{gas}) [KBOB 2016]

n: Life-cycle period considered [years] – (60 years)

Global Warming Potential (GWP): GHG emitted for the operation of the building and the construction materials (including the BIPV installation).

$$\text{GWP} = \text{GHG} + \text{CCF} \cdot \sum_{t=1}^{n} FEt$$

Where:

GWP-op: *Global Warming Potential (operational + materials) [$kgCO_{2\text{-}eq}/m^2 \cdot year$]*

GHG: GHG emitted due to the used materials (carbon emissions).

FE: Final energy consumption per type of energy source (electricity, oil or natural gas) [kWh]

CCF: Carbon Content Factor (Electricity: 0.102 $kgCO_{2\text{-}eq}$/$kWh_{e\text{-}pv}$, Oil: 0.301 $kgCO_{2\text{-}eq}$/kWh_{oil}, Natural gas: 0.228 $kgCO_{2\text{-}eq}$/kWh_{gas}) [KBOB 2016]

n: Life-cycle period considered [years] – (60 years)

Energy Payback Time (EPBT): required time for a complete BIPV renovation to compensate the primary energy consumed for its production and operation, considering the whole building life-cycle (60 years).

$$\text{EPBT} = \frac{\text{Total NRPE consummed}}{\text{Annual NRPE avoided due to renovation}} = \frac{NRPE}{\text{PEF} \cdot \sum_{t=1}^{n}(FE0t - FE1t)}$$

Where:

EPBT: *Energy Payback Time [years]*

NRPE: Non-renewable primary energy consumed (operational and construction phase) [kWh_{NRPE}] [KBOB 2016]

FE0: Final energy consumption (current status) of the building [kWh/year]

FE1: Final energy consumption (after renovation) of the building [kWh/year]

PEF: Non-renewable Primary Energy Factor (Electricity: 2.52 kWh_{NRE} /$kWh_{e\text{-}pv}$, Oil: 1.23 kWh_{NRE} /kWh_{oil}, Natural gas: 1.06 kWh_{NRE} /kWh_{gas}) [KBOB 2016]

n: Life-cycle period considered [years] – (60 years)

GHG Emissions Payback Time (GPBT): required time for a complete BIPV renovation to compensate the GHG emitted for its production and operation, considering the whole building life-cycle (60 years).

$$\text{GPBT} = \frac{\text{Total GHG emitted}}{\text{Annual GHG emissions avoided due to renovation}} = \frac{GHG}{\text{CCF} \cdot \sum_{t=1}^{n}(FE0t - FE1t)}$$

Where:

GPBT: *GHG Emissions Payback Time [years]*
GHG: Total GHG emitted [$kgCO_{2\text{-eq}}$] [KBOB 2016]
FE0: Final energy consumption (current status) of the building [kWh/year]
FE1: Final energy consumption (after renovation) of the building [kWh/year]
CCF: Carbon Content Factor (Electricity: 0.102 $kgCO_{2\text{-eq}}/kWh_{e\text{-pv}}$, Oil: 0.301 $kgCO_{2\text{-eq}}/kWh_{oil}$, Natural gas: 0.228 $kgCO_{2\text{-eq}}/kWh_{gas}$) [KBOB 2016]
n: Life-cycle period considered d[years] – (60 years)

10.6.4. Life-Cycle Cost (LCC)

Investment cost (I): Initial investment to conduct the whole renovation including public aids.

$$\text{I} = C_{REN} - S_{REN} + C_{BIPV} + S_{BIPV}$$

Where:

I: *Total investment cost of the renovation [CHF]*
C_{REN}: Renovation cost (construction materials and HVAC systems) [CHF]
S_{REN}: Subsidies for renovation [CHF]
C_{BIPV}: BIPV installation cost [CHF]
S_{BIPV}: Subsidies for BIPV installation [CHF]

Net present value (NPV): is determined by calculating the costs (negative cash flows), using the energy savings cost as incomes (positive cash flow) for a specific investment period.

$$\text{NPV} = \sum_{t=1}^{n} \frac{Ct}{(1+i)^t} - I_0$$

Where:

NPV: *Net Present Value [CHF]*
I_0: Initial investment cost [CHF]
t: Year of the cash flow [year]
n: Number of years in investment period [years]
i: Discount rate or interest rate received from an alternative investment found [%]
C: Net cash flow: difference between expenses (negative values) and energy cost savings (positive values) [CHF]

Internal rate of return (IRR): it is the interest rate (or discounted rate) that gives a NPV of zero. That means the minimum interest rate that is needed to receive in an alternative investment to equalise the investment in the renovation.

$$\text{IRR} = \text{i when NPV} = \sum_{t=1}^{n} \frac{Ct}{(1+i)^t} - I_0 = 0$$

Where:

IRR: *Internal rate of return [%]*
I_0: Initial investment cost [CHF]
t: Year of the cash flow [year]
n: Number of years in investment period [years]
i: Discount rate or interest rate received from an alternative investment found [%]
C: Net cash flow: difference between expenses (negative values) and energy cost savings (positive values) [CHF]

Discounted payback time (DPBT): it is the number of years to recover the investment cost taking into account as incomes the annual savings (compared to the current status of the building) and using the discounted-cash flow (DCF) method. The payback time corresponds to the period when the NPV becomes positive.

Simple payback time (SPBT): it is the number of years to recover the investment cost taking into account as incomes the annual savings (compared to the current status of the building) without considering any price actualisation.

Profitability rate with current rent (PRCR): ratio between the operational annual savings (compared to the current status of the building) and the total renovation cost.

$$\text{PRCR} = \frac{\text{Annual savings}}{\text{Investment cost}} = \frac{AS}{I}$$

Where:

PRCR: *Profitability rate with current rent [%]*

AS: Annual cost savings (operational phase) [CHF/year]

I: Initial investment to conduct the whole renovation including public aids [CHF]

10.7. Example of detailed LCA results

Figure 10-34 to Figure 10-37 illustrate the operational and construction LCA results (on the left) and the detailed LCA results regarding the contribution of the embodied energy and carbon of the renovation (on the right), decomposed per construction element (opaque surfaces, roof, windows, BIPV, etc.), for Archetype 1.

The elements having the larger weight in the CEDnr of renovation materials are opaque façade, BIPV, batteries, and, to a lesser extent, windows. In scenarios A-100%, BIPV dominate, particularly for S3-Transformation.

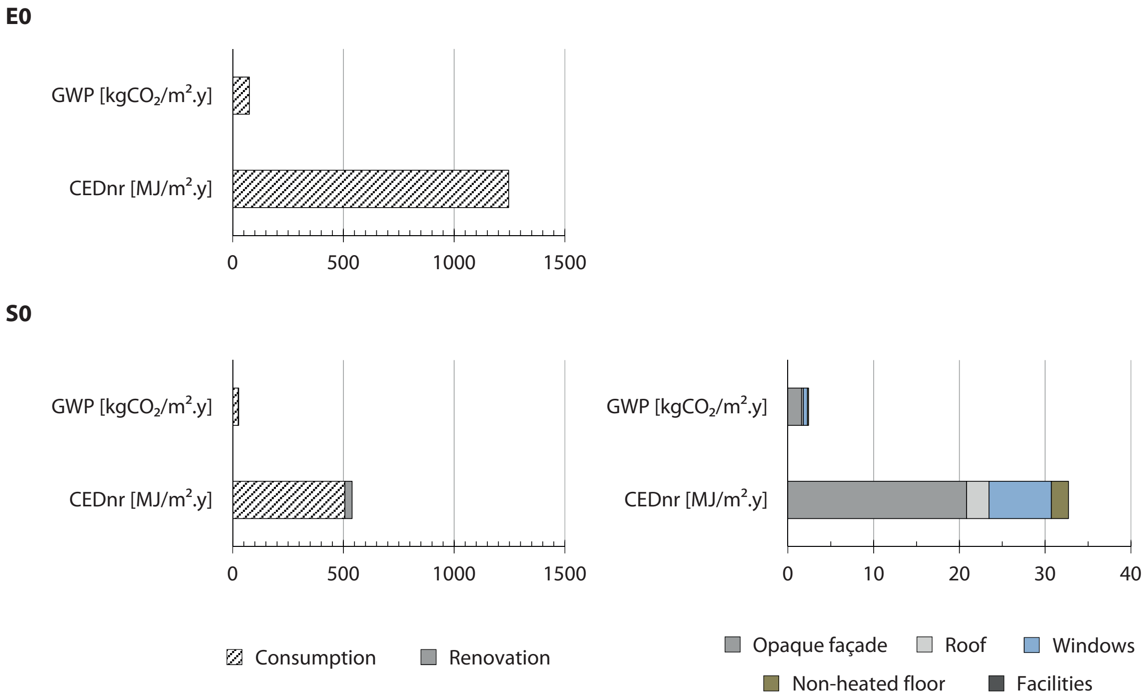


Figure 10-34. Operational and construction LCA (left) and decomposed construction LCA per element (right) for Archetype 1, E0-Current status (top) and S0-Baseline (bottom).

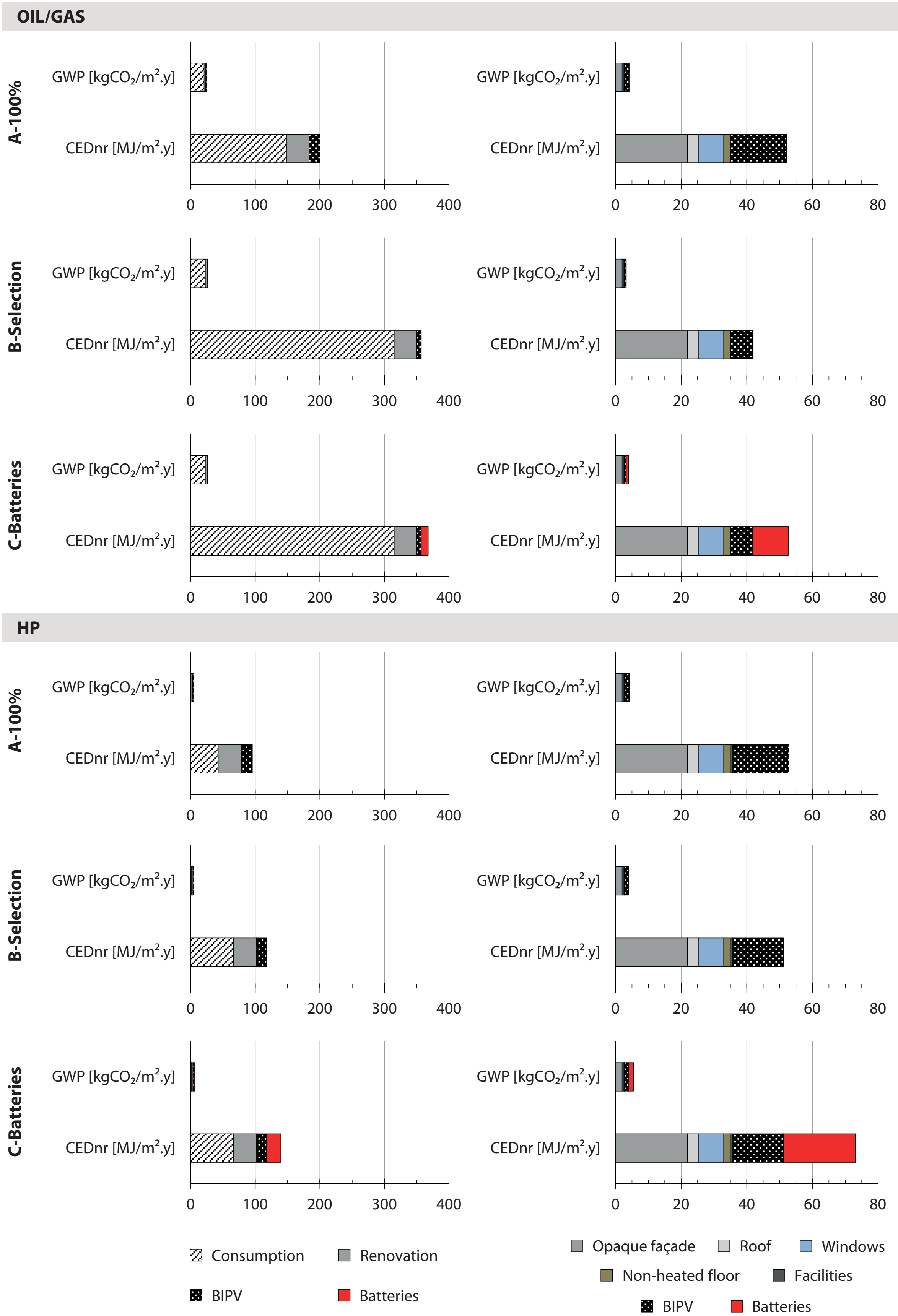


Figure 10-35. Operational and construction LCA (left) and decomposed construction LCA per element (right) for variants of Archetype 1, S1-Conservation, with injection.

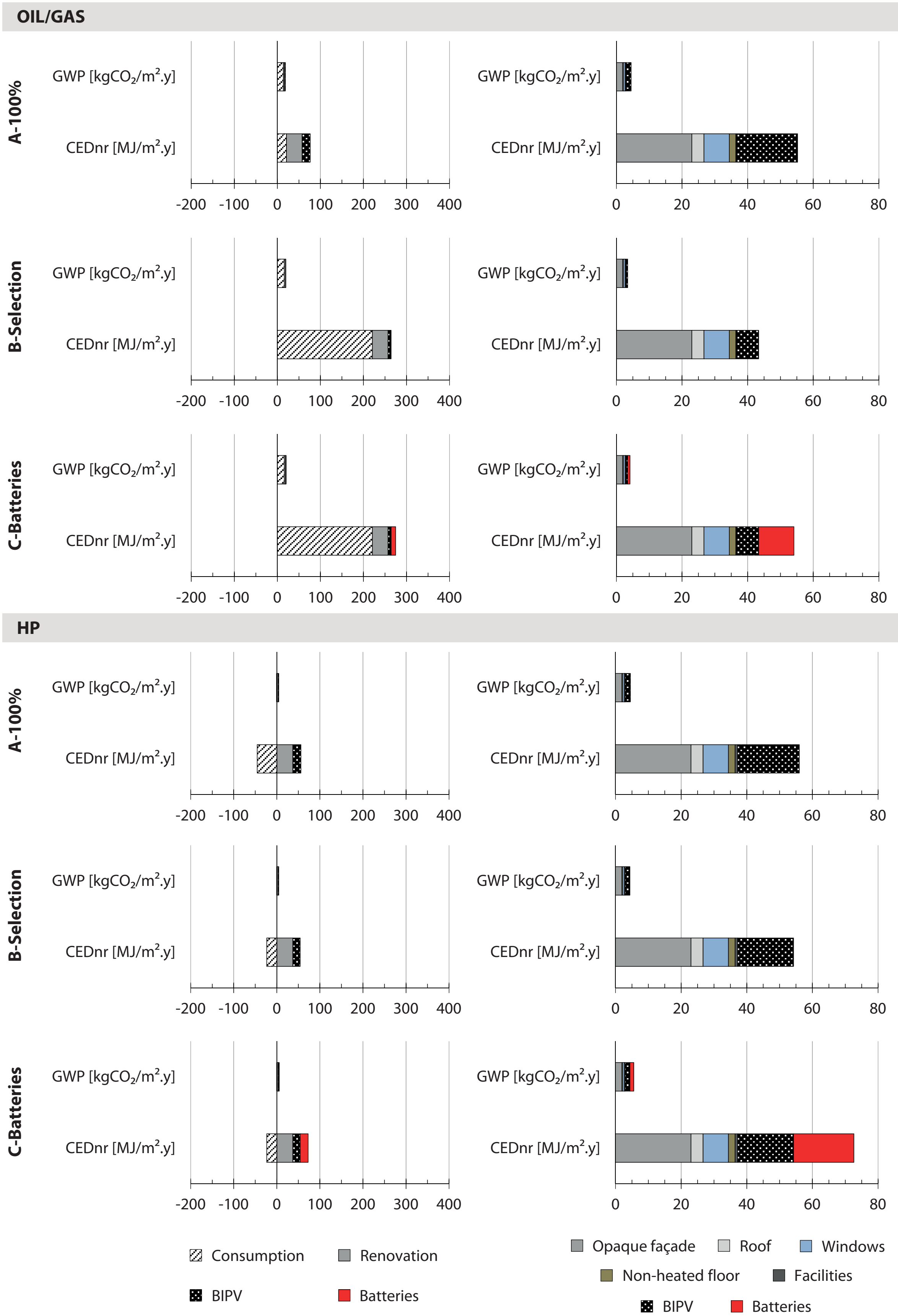


Figure 10-36. Operational and construction LCA (left) and decomposed construction LCA per element (right) for variants of Archetype 1, S2-Renovation, with injection.

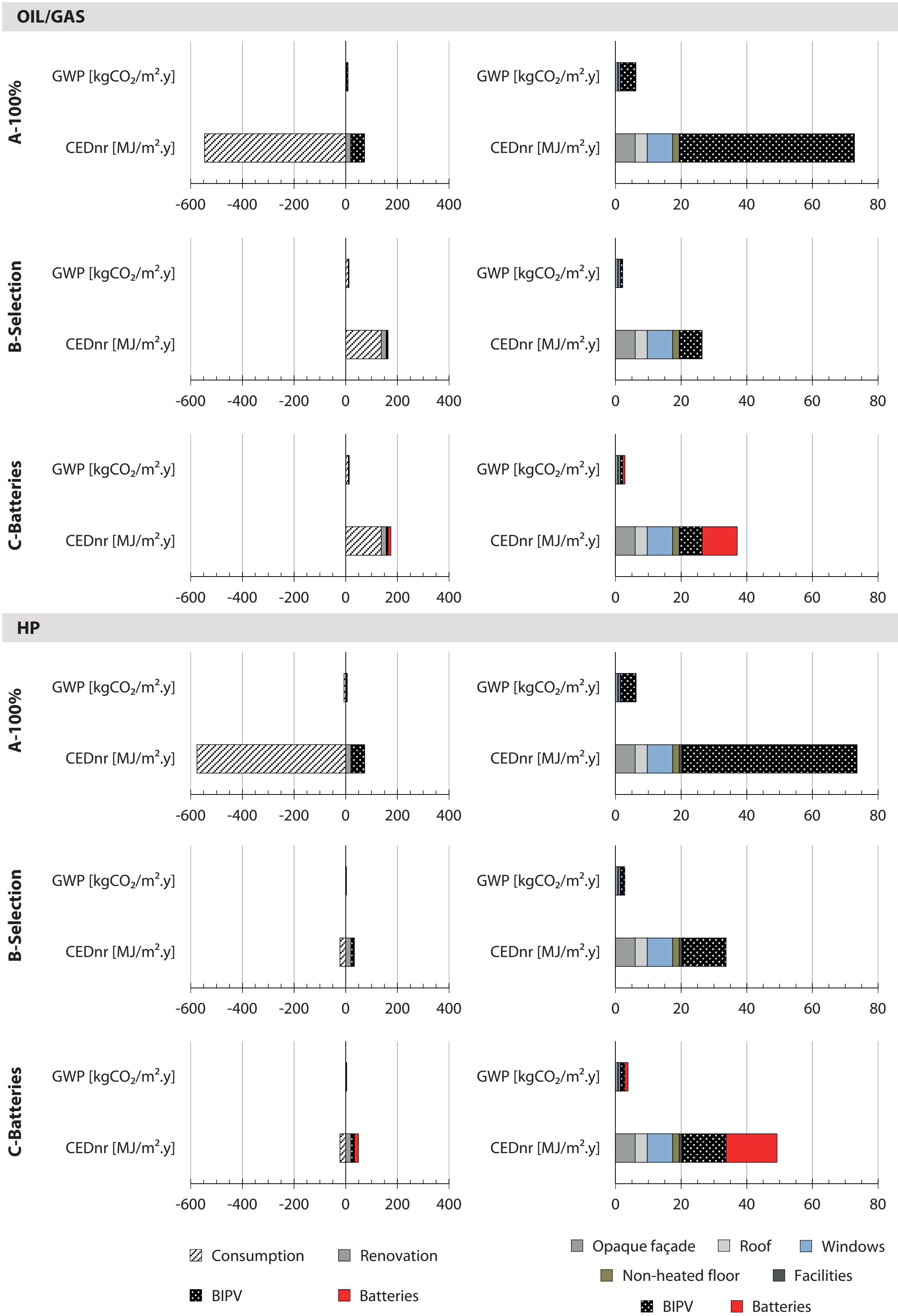


Figure 10-37. Operational and construction LCA (left) and decomposed construction LCA per element (right) for variants of Archetype 1, S3-Transformation, with injection.

Curriculum Vitae

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2013-2017	**Doctorate of Science** Universitat politècnica de Catalunya (UPC) School of Engineering (ESEIAAT)	Barcelona, Spain
2011-2013	**Master of Science in Architecture, Energy and Environment** Universitat politècnica de Catalunya (UPC) School of Architecture (ETSAB)	Barcelona, Spain
2004-2010	**Master in Architecture** Universitat politècnica de Catalunya (UPC) School of Architecture (ETSAV)	Sant Cugat del Vallès, Spain
1998-2004	**Master in Industrial Engineering | Mechanics** Universitat politècnica de Catalunya (UPC) School of Engineering (ESEIAAT)	Terrassa, Spain

PROFESSIONAL EXPERIENCE

2019-	**Building2050 group - smart living lab** Ecole Polytechnique Fédérale de Lausanne (EPFL) Manager of the integration of innovation in the building	Fribourg, Switzerland
2014-2019	**Laboratory of Architecture and Sustainable Technologies (LAST)** Ecole Polytechnique Fédérale de Lausanne (EPFL) Doctoral-assistant - teaching and reseach	Lausanne, Switzerland
2014-	**MARQuitectura - sustainable architecture** External consultant	Barcelona, Spain
2009-2014	**CABA Sustainability - energy engineers consulting** Project manager	Sabadell, Spain
2008-2009	**BOMA - structural engineers consulting** Project manager, renovation projects	Barcelona, Spain
2006-2008	**OBRAL - general construction company** Project engineer	Montcada i reixach, Spain
2003-2006	**DOMENECH ENGINYER - construction engineers consulting** Project engineer	Terrassa, Spain

TEACHING EXPERIENCE

2015-2018 **Teaching Unit - Architecture and Sustainability: Performance Studies**
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Teaching assistant

2016-2017 **Supervisor of master projects**
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Energy Management and Sustainability program (EMS)

2009-2015 **Supervisor of bachelor projects**
Universitat politècnica de Catalunya (UPC)
School of Engineering (ESEIAAT)

2012-2015 **Asociate professor - course coordinator**
Bachelor's degree in industrial design and product development engineering
Universitat politècnica de Catalunya (UPC)
School of Engineering (ESEIAAT)

SUPERVISED STUDENT MASTER PROJECTS

2017 A. Legrain; S. Vitali : Definition of design scenarios for the arrangement of tilted solar arrays and estimation of their electricity production from horizontal irradiances ; 2018.

M. I. Gaillet-Tournier; M. Desmarescaux : Assessing the viability of BIPV installations in building energy retrofitting projects ; 2017.

K. Siraganyan : Energy modeling of the Solar Decathlon pavilion: testing the thermal resilience under unplanned use ; 2017.

M. Desmarescaux; M. I. Gaillet-Tournier : Energy modeling of the Solar Decathlon pavilion: development and fine-tuning of solar passive strategies ; 2017.

AWARDS

2016 **Best poster award**
Sustainable Built Environment (SBE) regional conference, Zurich

2011 **Architectural competition**
2nd prize in « El Abrigo de tu hogar » by the ASA (Association of Sustainable Development and Architecture of Madrid)

2009 **Architectural competition**
2nd prize in the first phase of the national competition: Spain Schindler Award for Architecture, «Solutions for mobility and accessibility.» Project of a railway interchange at Plaza Catalunya in Barcelona.

PUBLICATIONS

Journals

2019 Aguacil S., Lufkin S. and Rey E. (2019). Active surfaces selection method for building-integrated photovoltaics (BIPV) in renovation projects based on self-consumption and self-sufficiency. Energy & Buildings, 193, 15-28, DOI: 10.1016/j.enbuild.2019.03.035

Drouilles J., Aguacil S., Hoxh E., Jusselme T., Lufkin S., Rey E. (2019). Environmental impact assessment of Swiss residential archetypes: a comparison of construction and mobility scenarios. Energy Efficiency (under review).

2017 Aguacil S., Lufkin S., Rey E. and Cuchi A. (2017). Application of the cost-optimal methodology to urban renewal projects at the territorial scale based on statistical data—A case study in Spain. Energy and Buildings, 2017, 144, 42-60, DOI: 10.1016/j.enbuild.2017.03.047

Conference papers

2018 Aguacil S., Lufkin S. and Rey E. (2018). Influence of design-decisions on the energy performance of renovation projects with building-integrated photovoltaics: Results for a 1968 residential archetype in Neuchâtel (Switzerland). In PLEA 2017, 34rd international Conference on Passive and Low Energy Architecture. Hong-Kong.

Aguacil S., Peronato, G. Lufkin S., Andersen, L. and Rey E. (2018). Assessment of the Building-Integrated Photovoltaic potential in urban renewal processes in the Swiss context: Complementarity of urban- and architectural-scale analyses. In PLEA 2017, 34rd international Conference on Passive and Low Energy Architecture. Hong-Kong.

Peronato, G., Aguacil S., Legrain, A., Rey E. and Andersen, L. (2018). Assessment of the Building-Integrated Photovoltaic potential in urban renewal processes in the Swiss context: Complementarity of urban- and architectural-scale analyses. In PLEA 2017, 34rd international Conference on Passive and Low Energy Architecture. Hong-Kong.

2017 Aguacil S., Lufkin S. and Rey E. (2017). Influence of energy-use scenarios in Life-Cycle Analysis of renovation projects with Building-Integrated Photovoltaics – Investigation through two case studies in Neuchâtel (Switzerland). In International Conference on Sustainable Design of the Built Environment. London, UK

Aguacil S., Lufkin S. and Rey E. (2017). Integrated design strategies for renovation projects with Building-Integrated Photovoltaics towards Low-Carbon Buildings: Two comparative case studies in Neuchâtel (Switzerland). In PLEA 2017, 33rd international Conference on Passive and Low Energy Architecture. Edinburgh.

Nault E., Aguacil S., Rey E. and Andersen M. (2017). Energy performance analysis in interdisciplinary education – Lessons learned from a simulation-based teaching approach. In PLEA 2017, 33rd international Conference on Passive and Low Energy Architecture. Edinburgh, UK.

Aguacil S., Lufkin S. and Rey E. (2017). Stratégies de rénovation active pour le parc bâti suisse. 9e Édition du Forum Ecoparc Potentiel solaire des territoires urbains : vers de nouveaux paradigmes ? TRACÉS dossier 11.2017. https://www.ecoparc.ch/nos-evenements/nos-forums/forum17/

2016 Aguacil S., Lufkin S. and Rey E. (2016). Towards integrated design strategies for implementing BIPV systems into urban renewal processes: first case study in Neuchâtel (Switzerland). Sustainable Built Environment (SBE) regional conference, Zurich, Switzerland.

2015 Aguacil, S., Lufkin, S., Rey, E. (2016). Architectural design scenarios with building-integrated photovoltaic solutions in renovation processes: Case study in Neuchâtel (Switzerland). In PLEA 2016, 32nd international Conference on Passive and Low Energy Architecture. Los Angeles, USA.

2018 Aguacil, S., Lufkin, S., Rey, E. (2015). Towards integrated design strategies for implementing BIPV systems into urban renewal processes: preliminary case study in Neuchâtel (Switzerland). In PLEA 2015, 31st international Conference on Passive and Low Energy Architecture. Bologna, Italy.

Conferences and talks

2018 Lufkin S., Aguacil, S. (2018). ACTIVE INTERFACES : Stratégie de rénovation active pour le parc bâti suisse ; Séminaire BIPV - NRP70, Neuchâtel, Switzerland, December 5.

Aguacil, S. (2018). Stratégie de rénovation active pour le parc bâti suisse. Cas d'étude à Neuchâtel ; Solar energy from buildings, between research and built reality, Lugano, Switzerland, November 14, Aguacil, S. (2018). Active renovation startegies for the Swiss building stock. Case study in Neuchâtel ; Swissolar Excursion, Lausanne, Switzerland, November 23.

Aguacil, S. (2018). Stratégie de rénovation active pour le parc bâti suisse. Cas d'étude à Neuchâtel ; Build & Connect - Technologies et pratiques pionnières du bâtiment, Strasbourg, France, November 28-29.

Drouilles, J., Aguacil, S., Lufkin, S. (2018). LOW CARBON HOUSING. Environmental impact assessment of Swiss residential archetypes : a comparison of construction and mobility scenarios ; smart living lunch, smart living lab, Fribourg, Switzerland, May 1.

2017 Aguacil, S. (2017). Life-cycle analysis of renovation projects with Building-Integrated Photovoltaics: Influence of energy use scenarios ; IDEAS Lunch | LAST - LIPID |Integrated Design, Architecture and Sustainability, École polytechnique fédérale de Lausanne, Switzerland, June 28.

2016 Aguacil, S. (2016). BIPV scenarios for facade retrofitting: challenges in architectural design ; ACTIVE INTERFACES 1st PhD Seminar, Lausanne, EPFL, April 11.

2015 Aguacil, S. (2015). Architectural design strategies for Building-Integrated Photovoltaics (BIPV) in urban renewal processes ; IDEAS Lunch | LAST - LIPID | Integrated Design, Architecture and Sustainability, École polytechnique fédérale de Lausanne, Switzerland, December 2.

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